PhD Research Dissertation

A CONCEPTUAL MODEL OF PHYSICAL PERFORMANCE IN AUSTRALIAN FOOTBALL

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Doctor of Philosophy

This thesis is submitted in fulfilment of the requirements for the Doctor of Philosophy

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Certificate of Authenticity

Except where explicit reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgment in the main text and bibliography of the thesis.

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Date

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Preface

The current project was established through an alliance in health and sports science between the University of Ballarat and the Essendon Football Club. This particular project enabled me to be embedded into the football department at Essendon Football Club to assist with the physical preparation program. Practically important fluctuations in physical performance are theorised to reflect alterations in fatigue or physical capacity. With a growing use of global positioning system technology in the elite Australian Football this project aimed to provide novel knowledge about its efficacy in facilitating a competitive edge.

The inspiration for this study came from a question reflecting the importance of the use of global positioning system technology for monitoring players' physical output in matches and training. The fundamental question raised was; "Which match exercise intensity variables are important to performance?"

This project took one year to develop and eighteen months to collect the data. The majority of the data comprised of elite Australian Football match analysis with a minority using recreational level Australian footballers. The project was divided into four studies separated into independent chapters within this dissertation. The data collection process occurred simultaneously for all studies whilst the drafting of chapters was progressive. One of the chapters has been represented in print (*Journal of Science and Medicine in Sport*) and two in press (*International Journal of Sports Physiology* and *Performance and Journal of Strength and Conditioning Research*) at the time of submission of this dissertation.

List of Article Submissions

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Mooney M, O'Brien B, Cormack S, Coutts A. Does physical capacity and interchange rest periods influence the match exercise intensity profile in Australian football? International Journal of Sports Physiology and Performance (In Press).

List of Conference Proceedings

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Mooney M, Cormack S, Coutts A, Berry J, O'Brien B. An analysis of work rate and match outcome in elite Australian Football. Australian Strength and Conditioning Association, 2009 (poster).

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Chapter 1: Introduction

Abstract

Objective: The objective of this project was to identify the relative influence of valid physical parameters to elite Australian Football performance.

Methods: Data was collected on match performance variables (i.e. coaches' votes, number of ball disposals, champion data rank), match exercise intensity measures ($m{\cdot}min^{-1}$, $m{\cdot}min^{-1}$ above and below 15 $km{\cdot}h^{-1}$ and Load™·min^{-1}) and physical capacities (yo-yo intermittent recovery test level 2, maximum oxygen uptake, running economy, relative aerobic intensity, maximal aerobic speed and maximal accumulated oxygen deficit) on elite and recreational Australian footballers. These variables were modelled to determine the logical sequence and relative importance towards match performance.

Results: The results indicate a sequential physical path to Australian Football performance. The yo-yo intermittent recovery test (level 2) performance influenced match exercise intensity ($m{\cdot}min^{-1}$ >15 $km{\cdot}h^{-1}$& Load™·min^{-1}) which in turn, affected Australian Football performance (number of ball disposals and coaches' votes). This sequence was altered by experience, playing position and neuromuscular fatigue. The number of interchange rotations also influenced match exercise intensity throughout the match. Furthermore, the yo-yo intermittent recovery test (level 2) was found to be determined by a complex interaction of physical capacities. However, yo-yo intermittent recovery (level 2) performance was most influenced by maximum oxygen uptake, relative aerobic intensity and maximum aerobic speed.

Conclusion: This dissertation showed Australian Football performance is a complex and dynamic system influenced by many variables interacting with each other in a sequential path. Sports scientists and coaches may utilise this information as a framework to evaluate Australian Football performance matches.

Operational Definitions

Disposals: A disposal is defined as a legal handball or kick performed during the designated playing time of an Australian Football match.

Elite Australian Football: Elite Australian football is defined as the national Australian Football competition the Australian Football League (AFL).

Global Positioning System (GPS): GPS is a portable device weighing approximately 100g that receives signals from several satellites and records the devices global location[1]. GPS identifies the athletes change in location and thus can determine the distance travelled and the rate of change in distance i.e. matches exercise intensity. Global positioning units house several inertial sensors including GPS, accelerometers for measuring subtle motion in 3 planes (X – medio-lateral, Y – anterior-posterior, Z – vertical), magnetometer for direction detection and gyroscope for rotation detection.

High Intensity Intermittent Endurance: The ability to perform intermittent sub maximal but high speed efforts with a short recovery period[2].

High Intensity Running: In this study high intensity running has been defined as distance travelled above 15 $km \cdot h^{-1}$. This is estimated to be equivalent to the ventilatory threshold found in elite soccer players[3].

Interchange: Substituting a player off the field with a replacement player.

Match Exercise Intensity: Match exercise intensity is an adapted term from "work rate" as cited previously in motion analysis literature[4]. It refers to the rate of locomotion during match play i.e. distance travelled per minute.

Australian Football Performance: Refers to the accumulated contribution of physical, tactical and technical performance.

Physical Capacity: Physical capacity is the performance outcome of an activity designed to predict a known physical attribute such as maximum oxygen uptake ($\dot{V}O_{2max}$), high intensity intermittent endurance and repeated sprint ability[5].

Physical Performance: The ability of an athlete to repetitively perform sport specific movements such as running, jumping, evasive movements, wrestling and pushing in Australian Football[6].

Repeated Sprint Ability: Repeated sprint ability is the ability to maintain a high speed during intermittent maximal effort of a short duration with an incomplete recovery[7].

Technical Performance: Technical performance refers to the performance of skill executions specific to the sport[8]. Technical performance specifically refers to how efficient players are getting and using the ball to the benefit of the team including effective disposals, tackles, marks and body positioning.

Tactical Performance: The ability to interact with other individuals during match play[6]. These specifically refer to players recognising the state of the match and positioning themselves accordingly, making effective decisions regarding their field position and use of the ball.

List of Abbreviations

~ = approximately

Δ = change in/of

β = beta weight

AFL = Australian Football League

ANOVA = Analysis of Variance

bLA = blood lactate

cm = centimetre

CO_2 = Carbon Dioxide

CV = coefficient of variation

e.g. = example

Eq. = equation

ES = effect size

et al. = and others

etc. = etcetera

FT:CT = flight time to contraction time ratio

g = gram

GPS = Global positioning system

h = hour

HIR = High intensity running

HIR $m \cdot min^{-1}$ = meters travelled at high intensity per minute

Hz = Hertz

i.e. = that is to say

kg = kilogram

km = Kilometres

$km \cdot h^{-1}$ = Kilometres per hour

L = litre

Load™·min^{-1} = accelerometer "load" per minute

m = meters

MAOD = maximal accumulated oxygen deficit

mm = millimetres

m·min^{-1} = meters travelled per minute

mL·kg^{-1}·min^{-1} = millilitres per kilogram per minute

mL O_2 eq.·kg^{-1}·min^{-1} = millilitres of Oxygen equivalent per kilogram per minute

n = number

NMF = neuromuscular fatigue

p = probability value

PCr = Phosphate creatine

pH = potential of Hydrogen

Pi = inorganic phosphate

pp. = page

Q = quarter

r = correlation coefficient

s = seconds

SD = standard deviation

SE = standard error

SPSS = Statistical Package for Social Sciences

TMA = time motion analysis

TTE = time to exhaustion

v. = version

vs. = versus

VO_2 = Volume of Oxygen

VO_{2I} = Volume of Oxygen inspired

VO_{2E} = Volume of Oxygen expired

$\dot{V}O_{2max}$ = Maximum oxygen uptake

Yo-yo IR1 = yo-yo intermittent recovery test (level 1)

Yo-yo IR2 = yo-yo intermittent recovery test (level 2)

Theoretical Framework

A conceptual model presented by Impellizzeri and Marcora[6] suggests soccer performance is comprised of three major sub-components of performance such as tactical, technical and physical performance (Figure 1.2). This conceptual model indicates that the ranking of the team is the aggregate of tactical, technical and physical performance. It also suggests that there are relevant measures of each of these constructs which are preceded by causal components such as physical capacity. Using this model allows coaches to measure relevant information that will have a direct or indirect impact on team rank. The yo-yo IR2 test has been identified as a causal indicator to the ability to perform high intensity activity in soccer players[8]. This suggests that the yo-yo IR2 has an indirect influence on team rank. Australian Football shares similarities in physical demands with soccer[9, 10]. Therefore, this model may be transferable to Australian Football.

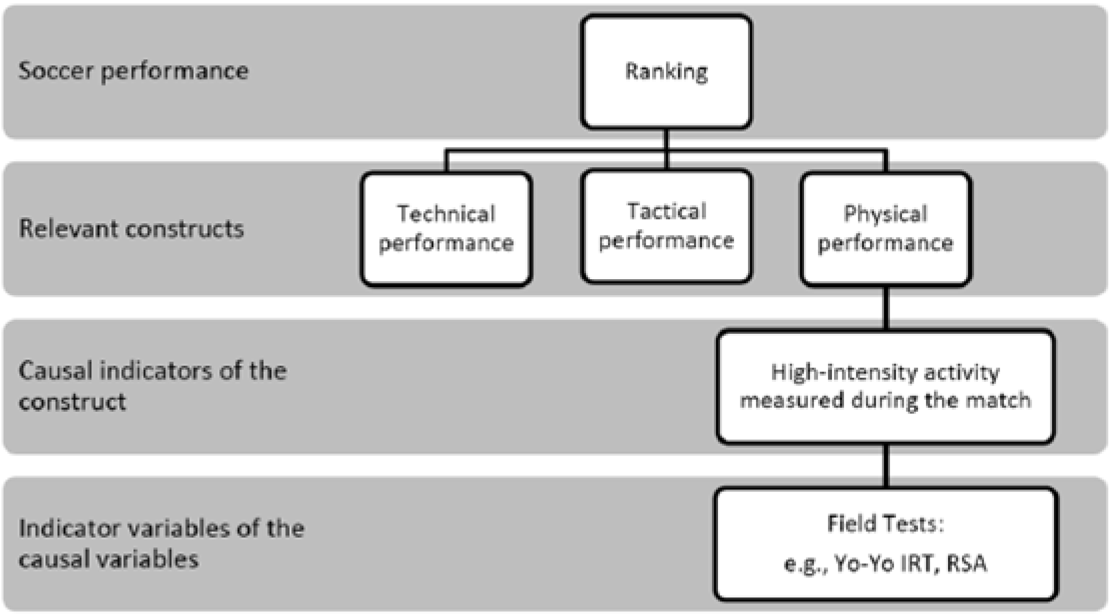


Figure 1.1: The current theoretical framework of soccer performance extracted from Impellizzeri and Marcora, pp. 271[6].

To elucidate the physical contribution to performance the fitness-fatigue model proposed by Banister and colleagues[11] was considered in the methodology. The fitness-fatigue model identifies fatigue as the limiting factor of the transfer of fitness to physical performance[11]. Neuromuscular fatigue (i.e. flight time, contraction time ratio) correlates negatively with Australian Football performance, and was chosen to represent a measure of fatigue in this model[12]. Neuromuscular fatigue is described as insufficient central neural drive or peripheral reductions in performance beyond the neuromuscular junction and may result in alterations in motor unit recruitment[13]. Cormack et al. found that neuromuscular fatigue has a normal fatigue-recovery cycle of 72 hours after an elite Australian Football match[14]. According to the fitness-fatigue model, if normal neuromuscular status is not restored, physical performance will suffer, assuming fitness has not changed.

The combination of these theories provided the theoretical rationale for these series of studies. Currently, the application of these models in Australian Football is yet to be investigated.

Overview of Research Project

The aim of this project was to identify the contribution of the selected physical parameters to Australian Football performance. This dissertation is a series of studies that investigated the interactions between physical parameters and elite Australian Football tactical, technical and physical performance, as shown in Figure 1.2. The major themes (highlighted in Figure 1.2) incorporate the relative contributions and interaction of physical capacity and fatigue, specifically neuromuscular fatigue, similar to that outlined by the fitness-fatigue model[11]. The first of four studies identifies the contribution of the yo-yo IR2 score to Australian Football performance in a mediation model at the beginning of the competitive season, whilst incorporating playing position and experience as conditional variables. The second study was a season long study that investigated the contribution of yo-yo IR2 to Australian Football performance incorporating neuromuscular fatigue as a conditional variable into the mediation model. The third study investigated the relative contributions between aerobic power and anaerobic capacity to yo-yo Intermittent Recovery test (level 2) capacity (yo-yo IR2). The final study investigated the impact of interchange rotations and yo-yo IR2 score on the profile of match exercise intensity throughout a match.

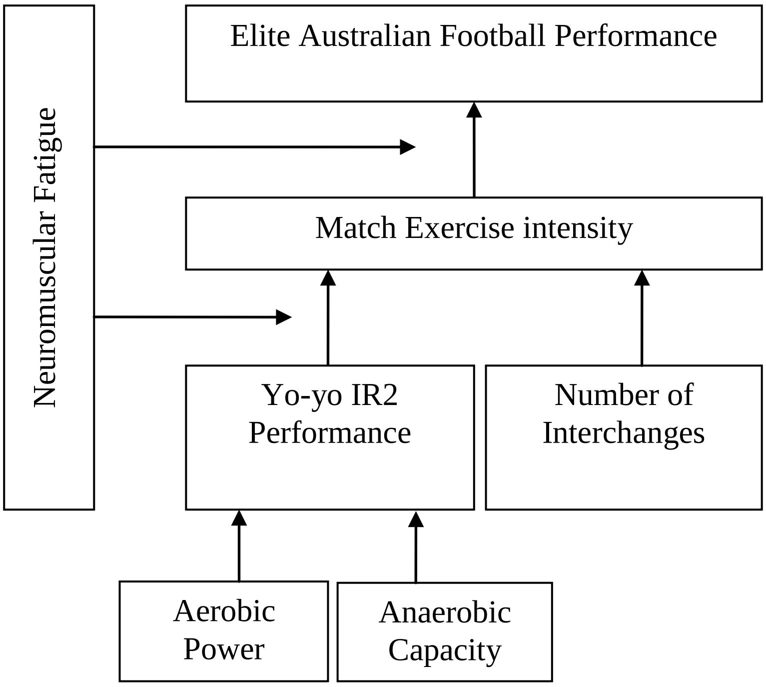


Figure 1.2: A schematic model of the major themes for this research project.

Significance of the Research

The questions addressed in this dissertation provide important empirical information regarding the application of the theoretical concepts, such as physical capacities that affect elite Australian Football performance. It is of vital importance to the field of sports science to "bridge the gap" between science and practise. By scientifically analysing the interaction of Australian Football performances and physical capacity this dissertation addresses current practical questions that have immediate application. Furthermore, this thesis contributes to a theoretical model incorporating a holistic performance analysis approach to elite Australian Football, focussing on physiological capacities, fatigue, tactical and technical analysis.

Establishing an Australian Football performance model from a physical perspective enables coaches and sports scientists to have an empirical foundation to base training practice, fatigue management systems and match day tactics. This model provides context to the relative importance of currently used physical performance measures and establishes a foundation for future aspects of Australian Football performance yet un-tested. It is important to consider this research as a starting point which incorporates the current theories in Australian Football performance, and combine them in one model for future research to build upon.

References

1. Larsson P. Global positioning system and sport-specific testing. Sports Medicine. 2003;33(15):1093-101.
2. Bangsbo J, Iaia FM, Krustrup P. The yo-yo intermittent recovery test: A useful tool for evaluation of physical performance in intermittent sports. Sports Medicine. 2008;38(1):37-51.
3. Abt G, Lovell R. The use of individualized speed and intensity thresholds for determining the distance run at high intensity in professional soccer. Journal of Sports Sciences. 2009;27(9):893-8.
4. Reilly T, Thomas V. A motion analysis of work rate in different positional roles in professional football match play. Journal of Human Movement Studies. 1976;2:87-97.
5. McArdle WD, Katch FI, Katch VL. Exercise physiology: Energy, nutrition, and human performance. Darcy P, editor. Philadelphia, Pennsylvania: Lippincott Williams & Wilkins; 2001.
6. Impellizzeri FM, Marcora SM. Test validation in sport physiology: Lessons learned from clinimetrics. International Journal of Sports Physiology and Performance. 2009;4:269-77.
7. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, Goodman C. Time motion analysis of elite field hockey, with special reference to repeated sprint ability. Journal of Sports Sciences. 2004;22(9):843-50.
8. Rampinini E, Bishop D, Marcora SM, Ferrari Bravo D, Sassi R, Impellizzeri FM. Validity of simple field test as indicators of match-related physical performance in top-level professional soccer players. International Journal of Sports Medicine. 2007;28:228-35.

9. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. Journal of Sports Sciences. 2003;21:519-28.

10. Wisbey B, Montgomery P, Pyne DB, Rattray B. Quantifying movement demands of AFL football using GPS tracking. Journal of Science and Medicine in Sport. 2010;13(5):531-36.

11. Banister EW, Calvert TW. Planning for future performance: implications for long term training. Canadian Journal of Applied Sport Science. 1980;5(3):170-6.

12. Cormack S, Newton RU, McGuigan MR, Cormie P. Neuromuscular and endocrine responses of elite players during an Australian Rules football season. International Journal of Sports Physiology and Performance. 2008;3:439-53.

13. Strojnik V, Komi PV. Neuromuscular fatigue after maximal stretch-shortening cycle exercise. Journal of Applied Physiology. 1998;84(1):344-50.

14. Cormack SJ, Newton RU, McGuigan MR. Neuromuscular and endocrine responses of elite players to an Australian rules football match. International Journal of Sports Physiology and Performance. 2008;3(3):359-74.

15. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I. Physical fitness, injury, and team performance in soccer. Medicine & Science in Sports & Exercise. 2004;36(2):278-85.

16. Young W, Newton RU, Doyle TL, Chapman D, Cormack S, Stewart G, et al. Physiological and anthropometric characteristics of starters versus non-starters and playing position in elite Australian Football: A case study. Journal of Science and Medicine in Sport. 2005;8(3):333-45.

Chapter 2: Literature Review

Introduction

Since the 1970's Australian Football coaches have been intrigued by the physical demands of Australian Football and the impact of physical fitness on performance[1, 2]. A systematic search of online database "PubMed" was completed using terms "Australian Football" and "Australian Rules Football" on the 3rd November, 2010. The search yielded 157 articles relevant to Australian Football, the overwhelming majority (95 or 61% of articles) investigated injury or medical aspects of Australian Football whilst 42 articles (27%) investigated either performance or physiological characteristics. Coaches are currently using contemporary methods in an attempt to improve physical performance through means of limiting the effects of fatigue or increasing fitness such as, exploring novel ways to improving physical capacity. However, coaches are also increasing club investment in order to analyse performance more efficiently and with greater detail to gather more "intelligence" about their own performance and the performance of opposition teams. For example each club has a subscription to match statistics software to analyse all matches in real time (Champion Data: CIA and CIS), most have licenses to video analysis software (SportsCode, Coda and Dartfish) and all clubs have access to real time Global Positioning System (GPS) technology (Catapult Sports or GPSports). These recent advances in technology have resulted in more efficient and reliable methods to collect a plethora of performance, match exercise intensity and physical capacity data to evaluate physical preparation programs and on-field performance[3-6]. This review of literature aims to investigate the importance of such information to better understand the impact of physical capacity and the influence of fatigue on Australian Football performance.

Physical Attributes of Australian Footballers

Australian Football is played on an oblique shaped field of varying sizes generally between 135 – 185 m in length by 110 – 155 m in width[7]. Players will score points by kicking the ball through the two large posts (goals) for six points and outside the larger posts but within the smaller posts (behinds) for one point. Two teams of 22 players with 18 players from each team taking the field at once, for 4 X 20 min periods (quarters) with additional time played for stopped play (approximately 10 min added). Each team may have four players on the interchange bench that can be freely rotated into the game without restriction. A recent rule change (brought in for the 2011 season) meant that one of the players on the interchange bench was nominated as a substitute and was only allowed to participate in the game at the permanent withdrawal of a team mate. A typical season lasts for 22 matches played once per week with one general bye, plus up to four finals match if the team finished in the top eight teams on the win/loss table. The season begins in March (autumn) and continues until a single match to decide the winning team (Grand Final) in September. Players are required to participate in a club driven 21 week preseason that includes four or more practice matches. The players may be allocated positions spread all over the field and are matched with an opponent of the contrasting position, for example, a full back player will play opposing the full forward player. Australian Football has been described as having a similar physical nature to both soccer (due to the running demands) and rugby (due to the tackling demands) [8].

Due to the unique physical demands of Australian Football, elite (AFL) footballers require a number of well-developed physical characteristics, and often an individual’s physical characteristics will distinguish positional role in the team[9]. Table 2.1 illustrates some of the physical attributes of Australian footballers reported in the literature. Elite Australian footballers have been reported to be getting taller and heavier at a rate of 1.2cm per decade and 1.3kg per decade, since 1910[10]. The mean stature and mass of an elite Australian footballer remains consistently above the general population, suggesting that among other physical traits, being taller and heavier is advantageous to play elite Australian Football[10]. This portion of the literature review will further focus on identifying the desirable physical attributes of elite Australian footballers.

Table 2.1: The mean physical characteristics of Australian footballers reported in the literature since 2005.

Authors	n	Competition Standard	Sum of 7 Skin Folds (mm)	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	v$\dot{V}O_{2max}$ (km·h^{-1})	Yo-Yo IR2 (m)	300 m Shuttle time (s)	IPRS (km·h^{-1})	20 m Sprint (s)
Pyne et al. (2005)[11]	283	Elite Junior	56.0	57.8					3.04
Young et al. (2005)[12]	34	Elite	52*	61		647			1.90^
Thomas et al. (2006)[13]	23	Elite		61.2		708			
Pyne et al. (2006)[9]	495	Elite Junior	55.3	57.8					3.04
Young & Prior (2007)[14]	485	Elite Junior		57.9					
Duffield et al. (2009)[15]	10	Elite		55.6					
Lorenzen et al. (2009)[16]	23	Elite		54.1	16.7				
Hunter et al. (2011)[17]	29	Regional		54.4			69	26.1	
Mooney et al. (2011)[18]	31	Regional						27	
	29	Sub Elite						27.4	
	10	Elite						28.6	

$\dot{V}O_{2max}$ = maximal oxygen uptake, v$\dot{V}O_{2max}$ = velocity at maximal oxygen uptake, IPRS = intermittent peak running speed, * = sum of eight skin folds, ^ = 10 m sprint time.

Anthropometric measurements

The anthropometric measurements of Australian footballers have been cited from the recreational level to the elite level. Figure 2.1 shows the reported stature and mass of Australian footballers in the literature, categorised by competition standards. Elite level players are similar in stature to elite junior players, although carry more mass[9, 11-20]. Furthermore, sub-elite players tend to be shorter and lighter than the elite population.

Some studies have focused on the anthropometrical status of Australian footballers, such as Pyne et al.[11] who investigated the career progression of elite junior players based on their anthropometric measurements. This study analysed 283 elite junior footballers at the national draft camp, where Australian Football League (AFL) clubs invite junior players to participate in a battery of tests to aid in recruiting. This study found only trivial relationships between anthropometric values and career progression, suggesting anthropometric status of junior level players may not assist their performance at senior standards. Furthermore, Young et al.[12] also evaluated the difference in anthropometric measurements of an AFL team between playing positions and starters vs. non-starters (selected and non-selected). It was reported that stature and mass could not distinguish between starters and non-starters or playing position at the elite standard, however, mid-field players had a significantly lower sum of seven skin folds than forwards[12]. Pyne et al.[9] categorised positions differently to Young et al.[12] reporting positions based on physical appearance and playing position such as small mid-field, medium mid-field, medium defenders, medium forwards, tall forwards and rucks with distinct differences in stature and mass. Although Pyne et al.[9] reported the stature and mass were different in this study, the sum of seven skin folds did not indicate any variations across positions suggesting that all positions have similar body fat levels. Anthropometric measurements clearly have the ability to characterise playing position and may be a useful indicator in talent identification processes. However, no clear correlation between stature, mass or body fat levels is evident to individual ability, thus it is advantageous to be taller heavier and leaner but not critical.

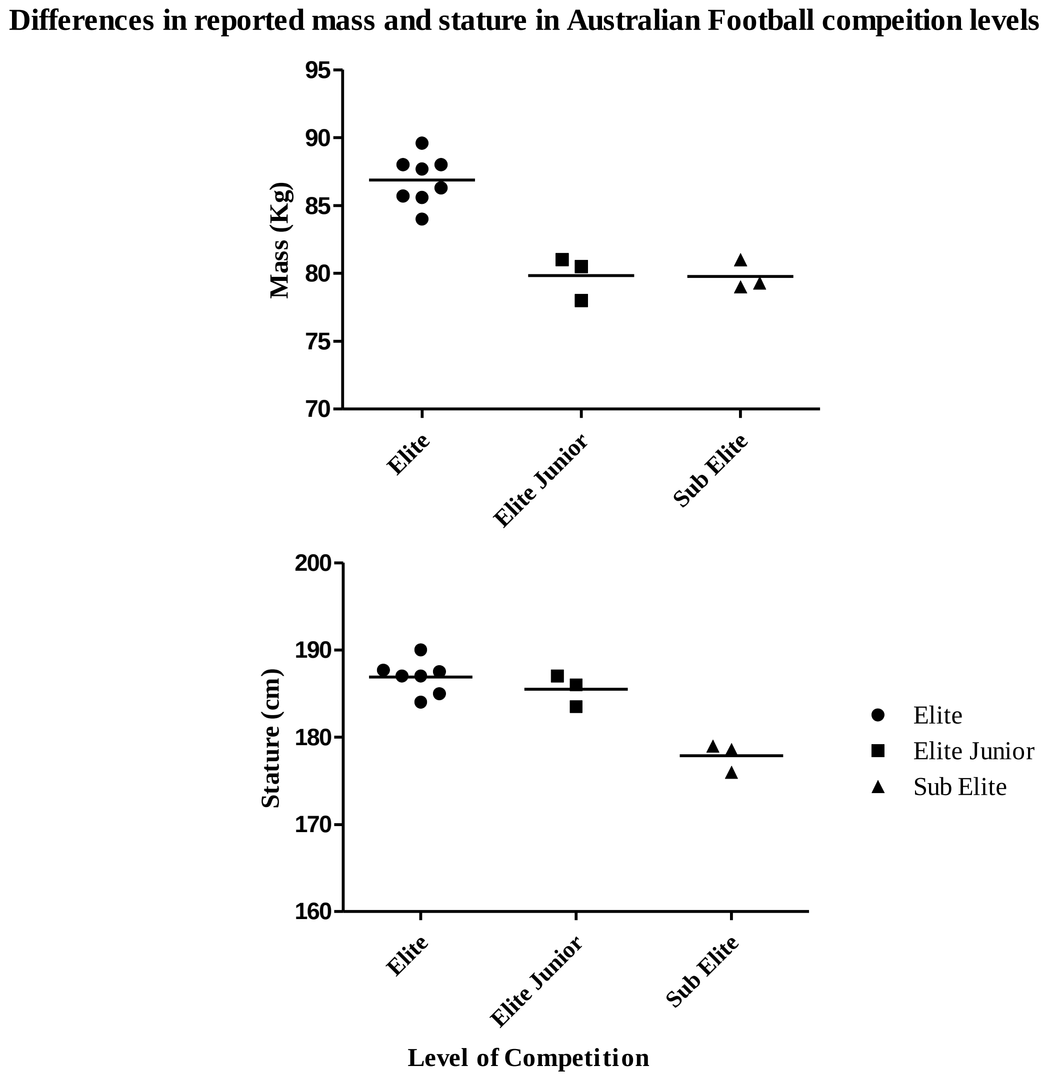


Figure 2.1: The differences of reported stature and mass between levels of competition in Australian Football. The horizontal line in each data set represents the mean of the surrounding data points[9, 11-20].

Physical Capacity of Australian Footballers

For a physical capacity to be a valid indicator of an Australian footballer's physical performance it must be specific to the sport, and undergo a series of validation analyses[21]. Currently, the tests that have provided evidence of validity in Australian Football (often construct validity) have been predicted $\dot{V}O_{2max}$ from the multi-stage shuttle test, high intensity intermittent endurance from the yo-yo IR2 test and repeated sprint ability from the intermittent peak running velocity test[12, 18]. These capacities have currently shown that in isolation they are desirable traits in elite Australian footballers. Currently coaches and sports scientists have a reasonable understanding of why these traits are desirable but little is known about how they impact on performance.

Aerobic Power

Aerobic power assesses the athlete's capability to supply oxygen to working musculature[22]. The rationale to test maximal aerobic power in Australian Football is based on the cardiovascular model of fatigue[23]. The cardiovascular model suggests that performance is limited by the ability of the cardiovascular system to supply enough oxygen to support the energy demand of the activity, thus the greater the maximal aerobic power the greater the potential performance[24]. Due to the length of an Australian Football match (approximately 120 minutes) this rational has face validity as utilising predominately anaerobic metabolism is unsustainable for a match of this duration. Furthermore, the key substrates/metabolites from anaerobic metabolism require oxygen to be present in order to regain homeostasis[22]. This has provided the ideology of the contribution of aerobic power to performance[1].

Jaques and Pavia were the first to assess the association of aerobic power and running performance in Australian Football by correlating the rank of estimated total distance travelled and rank of estimated aerobic power assessed by the Astrand protocol[1]. A moderate correlation was found suggesting that aerobic power may be an important characteristic in on-field running performance ($r = 0.66$ $p < 0.01$). However, several limitations of the study including, but not limited to, the accuracy of the Astrand protocol to determine aerobic power[25] and the method in estimating distance travelled (based on assuming no change in distance across quarters)[19] make the results difficult to generalise to the current elite cohort.

Maximum oxygen uptake ($\dot{V}O_{2max}$) provides an indication of aerobic power and the function of the cardio-pulmonary and neuromuscular systems[22]. Estimated $\dot{V}O_{2max}$ measured via the multi stage shuttle test has been reported previously in Australian Football for division one country footballers[17], elite junior footballers[11] and elite senior footballers[12]. Young et al.'s study of 34 elite Australian footballers from a single AFL team found there was a small difference in $\dot{V}O_{2max}$ of starters versus non-starters (effect size = 0.34)[12]. This suggests that a greater aerobic power is advantageous in Australian Football players at the elite level.

Maximum Oxygen uptake in elite Australian footballers is reportedly similar to elite soccer players[16, 26]. A landmark study by Helgerud et al.[27], in soccer, found that an increase in $\dot{V}O_{2max}$ (~10%) and running economy (~7%) was synchronised with an increase in total distance travelled (~ 20%) during a simulated soccer match. Although these results do not indicate a causal relationship between $\dot{V}O_{2max}$ and distance travelled, it indicates athletes with a greater $\dot{V}O_{2max}$ may use this characteristic to travel a greater distance. Although $\dot{V}O_{2max}$ is a valid measure of aerobic power, recent studies in running based sports have focused on maximal aerobic speed (MAS) and running economy as discriminators of running performance[28, 29]. Maximal aerobic speed predicts 5000m time trial performance much better than $\dot{V}O_{2max}$[30].

To date, few studies have assessed maximal aerobic speed or running economy in Australian footballers. Currently, one study has been conducted measuring MAS using indirect calorimetry in elite Australian footballers[16]. Lorenzen et al.[16] found a strong correlation between MAS and 1500 m and 3200 m time trial in elite Australian footballers ($r^2 = 0.63$). However, it was suggested that time trial performance and MAS should not be used interchangeably in elite Australian footballers, as the relationship is not strong enough to predict MAS[16]. Rather, research has indicated $\dot{V}O_2$ and running speed are not strongly correlated in elite-endurance athletes, suggesting other physiological factors such as running economy may also be an important factor in determining MAS[29]. In Australian Football it is well documented that athletes need to perform repeated high intensity efforts often above their MAS[31]. As expected $\dot{V}O_{2max}$ has shown to be a small discriminator of starters vs. non-starters in elite Australian Football as many other factors appear to influence the running performance particularly at high intensity[12]. Other aerobic based measures such as MAS and running economy should be considered when evaluating endurance characteristics.

High Intensity Intermittent Endurance

Popular tests of high intensity intermittent endurance are the yo-yo intermittent recovery (yo-yo IR) protocols. The yo-yo intermittent recovery (level 1) (yo-yo IR1) is similar to the multi-stage shuttle test with the exception of a short recovery period between shuttles and a faster progression of running speed. The yo-yo intermittent recovery (level 2) (yo-yo IR2) is a significantly faster version of the yo-yo IR1 and was developed for highly trained athletes, the procedures of these protocols have been described in a detailed review by Bangsbo et al.[3]. The yo-yo IR tests have been tested for reliability with typical errors ranging from 4.9% - 10.4% for a range of sports and standards[3].

The yo-yo IR1 and IR2 maximally stress the aerobic energy system and considerably stress the anaerobic energy systems, as participant's experience: maximum heart rate, heightened lactate production, reduced phosphate creatine concentration ([PCr]), reduced muscular pH and reduced bi-carbonate concentration[26]. Due to the difference in progressive speeds of the two tests, the yo-yo IR1 test predominately evaluates an athlete's maximum aerobic power, whereas the yo-yo IR2 evaluates the athlete's ability to utilise both aerobic and anaerobic energy systems[26]. Both tests show only moderate correlations with $\dot{V}O_{2max}$ (yo-yo IR1: r = 0.70; yo-yo IR2: r = 0.58)[3]. Although the yo-yo IR2 performance shows non-significant correlations with 50m sprint performance (r = 0.21) and repeated sprint ability (r = 0.26) the magnitude of the correlations may be practically important[32,33]. This highlights that the yo-yo IR2 test requires a unique combination of sports specific physical traits (e.g. agility) and the co-ordination of all energy systems similarly seen in soccer and Australian Football[12, 21].

Krustrup et al.[32] investigated the relationship between the yo-yo IR1 test and amount of high intensity running performed by elite soccer players. This study found a moderate to large significant relationship between high intensity running and distance covered during the yo-yo IR1 test ($r = 0.71$). This information was complemented by Mohr et al.[34] who found high class soccer players (professional players of a top 10 team) performed more high intensity running and also performed better at the yo-yo IR1 test than moderate class players (professional players of top 20 teams). However, the relationship between high intensity intermittent endurance and match exercise intensity in Australian Football remains unknown.

To date, high intensity intermittent endurance as assessed by the yo-yo IR2 has distinguished between starters and non-starters of an elite Australian Football team ($p = 0.02$)[12]. Furthermore, other associated variables to the yo-yo IR2 performance were correlated with votes awarded by the coaching staff (5 & 10 m sprint times) and number of ball possessions ($\dot{V}O_{2max}$, 5 & 10 m sprint times)[14]. Therefore, the yo-yo IR2 also shows promise as a valid physical performance predictor in Australian Football.

Anaerobic Capacity

Anaerobic capacity is the ability of the skeletal muscle to produce force without the presence of oxygen[22]. Producing force anaerobically has been shown to be unsustainable for gross movements such as sprinting and cycling[35]. Team sports often rely on short duration high intensity efforts requiring energy from anaerobic sources[36]. Repeated sprint ability has been used in research testing batteries in intermittent team sports such as soccer, hockey and Australian Football to assess aspects of anaerobic capacity[18, 37, 38]. Laboratory based studies have indicated that repeated sprint ability is a unique characteristic to aerobic power specifically $\dot{V}O_{2max}$[36]. However, $\dot{V}O_{2max}$ can influence sprint speed decrement in some protocols i.e. 6 X 6 s cycling[39]. Repeated sprint ability is restricted by the athlete's ability to limit PCr degradation and inorganic phosphate (Pi) accumulation[36]. Full PCr restoration and Pi removal are dependent on 1) the presence of oxygen and 2) the level of depletion of PCr and total accumulation of Pi[35, 36]. Given those with a greater aerobic power have a greater capacity to deliver, extract and utilise O_2 it is not surprising that $\dot{V}O_{2max}$ is associated with sprint speed decrement.

The intermittent peak running speed test was developed as a test of repeated sprint ability in Australian Football with promising results showing acceptable reliability (Coefficient of Variation, CV = 2.2%) and construct validity (4.2%, $p = 0.00$ difference between elite and sub elite) for mean sprint speed[18]. This test required athletes to perform 10 × 40 m sprints from a self-paced rolling 20 m start every 25 s in order to obtain peak velocity. This protocol was tested against other field tests to identify commonalities with $\dot{V}O_{2max}$, peak running velocity and estimated anaerobic capacity (using a 300 m shuttle test)[17]. The estimated anaerobic capacity test showed the strongest association with intermittent peak running velocity ($r = -0.88$, $r^2 = 0.77$), whilst $\dot{V}O_{2max}$ showed a moderate relationship ($r = 0.66$, $r^2 = 0.43$). The association between intermittent peak running velocity and $\dot{V}O_{2max}$ was likely due to a large amount of repetitions as aerobic energy yield can begin to dominate as early as three repetitions in all out repeated sprint tests[40]. The large correlation with 300 m shuttle test and peak running speed (r = -0.88 and 0.73 respectively) suggests that a high repeated sprint ability requires an enhanced anaerobic capacity. Other repeated sprint (6 × 40 m) protocols show strong correlations with yo-yo IR1 performance before and after ten repeated sprint training efforts (r = 0.74 and r = 0.86)[41]. The validity of the repeated sprint tests show that having hybrid physical capacities such as aerobic power (i.e. $\dot{V}O_{2max}$ as discussed earlier) and anaerobic capacity maybe beneficial to Australian Football performance.

The 300 m shuttle is a useful estimate of anaerobic capacity with moderate relationship with maximal accumulated oxygen deficit (MAOD) (r = -0.69)[42]. Maximum accumulated oxygen deficit is a measure of anaerobic capacity based on the assumption of a linear translation between speed and O_2 cost while running[43]. Despite the questionable accuracy of MAOD to determine anaerobic capacity, it appears to be a much more accurate and reliable method than oxygen debt, blood lactate (bLA) and PCr analysis[44]. Maximal accumulated oxygen deficit has a significant positive correlation with time to exhaustion at maximal aerobic speed (r = 0.63)[45]. However, the importance of anaerobic capacity has yet to be investigated in Australian Football.

Match Exercise Intensity in Australian Football

Measuring Exercise Intensity in Australian Football

Since the 1970's coaches and sports scientists have used a variety of methods of time motion analysis to measure match exercise intensity in team sports such as soccer[46], Australian Football[1] and hockey[47]. Manual time motion analysis has been the traditional method of determining match exercise intensity using drawings, plots or audio recordings of an observer[48, 49]. Prior to the analysis the mean speed was recorded from the individual athletes whilst standing, walking, jogging, running and sprinting[50]. Many limitations have been observed with this method of analysis; such as questionable inter-observer reliability, lack of validity of the estimated distances travelled at particular speeds or movements, requirement of skilled and experienced observers and the laborious nature of the analysis[51].

Global positioning system (GPS) technology was introduced as a means of collecting large amounts of match exercise intensity data quickly and accurately, and in many ways overcomes the limitations of traditional manual time motion analysis. Therefore GPS is the most popular time motion analysis device used to measure match exercise intensity in Australian Football. Commercially available GPS devices currently in use in team sports each house four independent internal sensory receivers that detect player motion including satellite antennae, accelerometer, magnetometer and gyroscope. The satellite antennae receive frequent updates on the athlete's global location from signals emitted by up to 27 satellites orbiting the Earth[52]. The athlete's global positions are then downloaded to purpose developed software capable of converting changes in global positions to speed. The sample frequency of present GPS models varies between one and ten Hertz (Hz), depending on model and manufacturer, however all units were deemed to have acceptable accuracy to detect total distance travelled[4, 6, 53].

The accuracy of GPS to measure distance at different speeds, like manual methods of time motion analysis, remains a technological issue. Researchers have found the shorter the running trial (i.e. 10 m vs. 40 m) the larger the inter-unit variability (i.e.

sprinting – 10 m CV = 30.9%, vs. 40 m CV = 11.9%)[4, 6]. Consequently, the capability of GPS to accurately gauge short sprints, accelerations and decelerations is questionable. Jennings et al. found inter-unit reliability during 20 – 40 m movements (ranging from walking to sprinting) was consistent (CV = 9.0 - 12.9%), whilst acceleration movements (i.e. 0 – 10 m) showed the poorest reliability (CV = 21.3 – 30.9%)[6]. These findings have been replicated in court sport specific activities[54]. Furthermore, more global team sports specific movements revealed acceptable validity for a sports specific grid run that incorporated different locomotion modes (CV = 1.8 – 3.8%) (See Figure 2.2)[4, 6]. Recently, the intra-unit reliability for the 10 Hz (MinimaxX, Catapult Sports, Scoresby, Australia) was reported as CV = 1.3% for 15 m sprint whereas the 5 Hz version from the same company has been reported a CV = 23.0% for a 20 m sprint[8, 50]. Enhancements in sample frequency, firmware and hardware have clearly improved GPS reliability and therefore knowledge of the reliability of the GPS units used is imperative both in research and practical settings[6].

In light of the current evidence in the literature GPS are currently able to reliably detect global movement across large distances, whilst individual accelerations are un-reliable. However, Aughey found the number of maximal accelerations can change by 97% in elite Australian Football finals matches and suggested the error associated with the detection of maximal accelerations was smaller than what has been observed between some matches[55]. Although the number of maximal accelerations was increased substantially in finals matches the ability of GPS to accurately detect a maximal acceleration remains questionable[4,6,54,55]. A significant improvement in the sensitivity of the devices to detect more subtle movements would be required to utilise accelerations as a match activity parameter.

The reliability of GPS has been investigated as new technology is released, with promising improvements from 1 Hz to 10 Hz [6, 53]. However, advances in technology makes comparing different models of GPS unreliable[4]. Even when comparing GPS devices that sample at the same frequency Coutts and Duffield found significant differences between GPS models (manufactured by the same company)[4]. Randers et al. also found distinct differences between methods of motion analysis including semi-automated multiple camera systems, time motion analysis and GPS[56]. When distance was presented as a percentage of the first 15 minutes of match play the systems showed agreement. This suggests ensuring reliability of exercise intensity analysis requires use of the same system and GPS model.

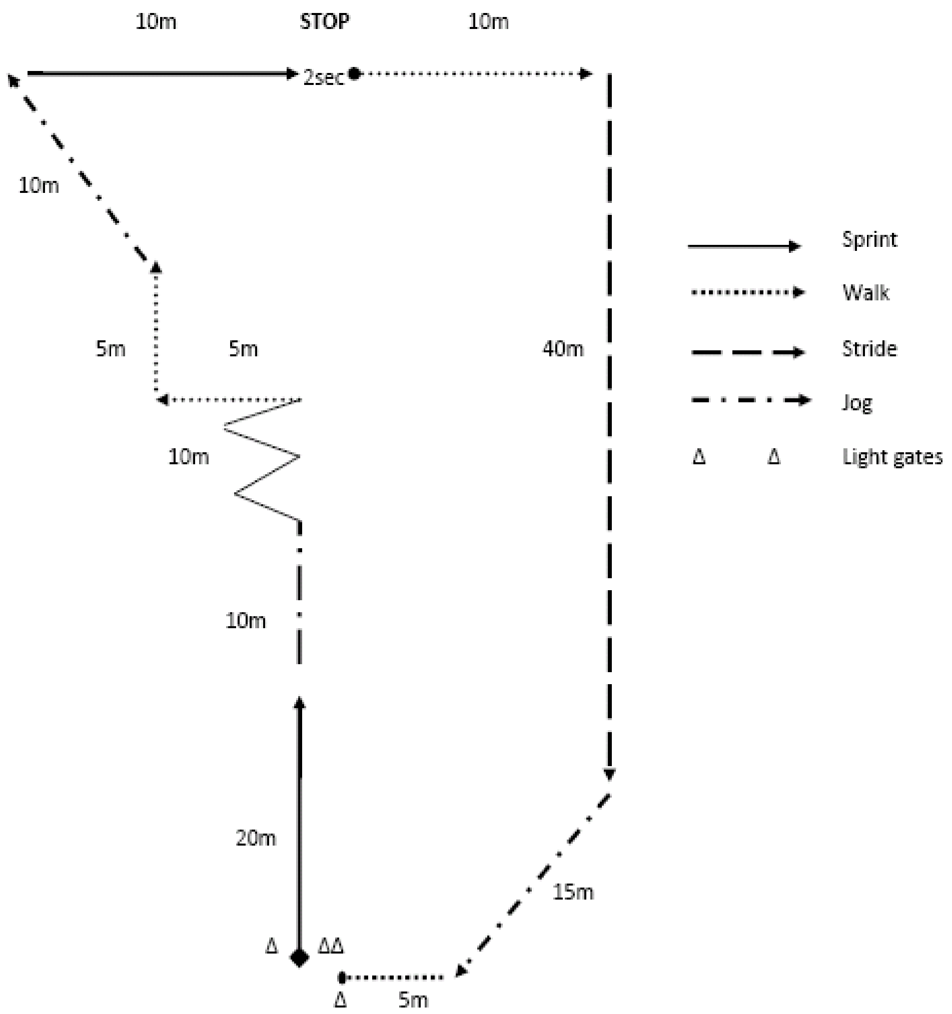


Figure 2.2: Team sport circuit used to test intra-unit reliability in Coutts & Duffield and Jennings et al.[4, 6].

To overcome the limitations of GPS in detecting subtle movements and needing visual access to satellites, accelerometers have been used to evaluate match exercise intensity in Australian Football[57] and basketball[58]. Accelerometers are small devices that can measure movement indoors and are popular tools for measuring physical activity in special populations, i.e. school children[59]. In team sport these inertia sensors are housed inside a GPS unit that detect accelerations/decelerations based on the change of inertia of the unit that is attached to the athlete (often on the upper back). The accelerometers used in Australian Football and basketball are tri-axial accelerometers that detect movement in three axis (medio-lateral, anterior-posterior and vertical) [57, 58]. The ability to detect acceleration in all three vectors provides a more holistic view of movement compared to GPS, which only detects displacement in two vectors with greater natural variability. Accelerometers are a more sensitive (measuring at 100 Hz) and reliable tool than GPS, with an inter-unit CV of 1.9%[57]. Due to the sensitivity and reliability of the accelerometers, accelerometers placed on the rear trunk show positive signs of detecting changes in centre of mass and may detect components of the running cycle (i.e. approximate foot contact time), with similar patterns shown in in-sole pressure sensors[60]. However, further research is required to identify the practical use of this in field based sports.

Match Exercise Intensity Variables

Total distance has been used in team sport as a primary measure of match exercise load providing coaches with an indication of the overall physical demand of a match (see Table 2.2)[46]. Total distance has been cited in elite level "football" codes such as soccer, rugby league, rugby union and Australian Football using a range of techniques. Recent research in elite soccer has reported total distance from 10.7 – 12.2 km[61, 62], rugby league has recently reported distances of 4.3 – 6.3 km[63,64], similarly rugby union has reported 5.5 – 6.1 km[65]. These studies provide practical insight into the physical demands of each sport, which has since allowed coaches to design training regimes more specifically tailored to their sport.

Jaques and Pavia[1] were the first to estimate the total distance travelled in Australian Football, reporting an estimated distance covered of 9.5 km in a match. Australian Football has evolved substantially since Jaques and Pavia's study. For example, the game has become a national competition with fully professional players, rule changes have been included such as abolishing the fixed number of player interchanges allowed per match, and increasing the number of available interchange players. Later Dawson et al.[66] found playing position influenced distance travelled in Australian footballers, ranging from 13.6 km for full forwards to 17.0 km for mid-fielders. Wisbey and colleagues [2, 67] have more recently reported much lower total distances for players. A notable reduction in mean total distance per player than reported by Dawson et al.[66], demonstrating a trend for players to be travelling less total distance over the last eight years (see Table 2.2). Differences in measurement techniques may have accounted for some of the variation[56]. However, tactical changes in the game, such as greater interchange rotations (AFL mean per team per match 2003 = 23 vs. 2010 = 92; unpublished data, Champion Data, Melbourne, Australia), may have resulted in less time spent on the field and a reduction in distance travelled. Increasing the rate of player rotations it has been thought, by coaches, to allow players to play at a greater intensity for longer periods of time and that this would offer a tactical advantage. Currently there is dearth of literature to support this theory.

Table 2.2: Total Distance reported in Australian Football.

Authors	**n**	**Level of Competition**	**Technique**	**Total Distance (km ± SD)**
Jaques & Pavia (1974)[1]	20	State	TMA	9.5
Dawson et al. (2004)[66]	11	Elite	TMA	13.6 - 17.0 (position dependant)
Wisbey & Montgomery (2006)[67]	52	Elite	GPS	12.45 ± 1.65
Veale et al. (2007)[68]	9	Junior Elite	TMA	9.2 – 11.87 (position dependent)
Veale et al. (2007)[69]	30	Junior Elite	TMA	9.8 - 17.0 (position dependant)
Wisbey & Montgomery (2007)[70]	80	Elite	GPS	12.51 ± 1.71
Wisbey et al. (2008)[71]	745	Elite	GPS	12.03 ± 1.9
Duffield et al. (2009)[15]	10	Elite (pre-season)	GPS	9.4 ± 1.47
Wisbey et al. (2009)[7]	1395	Elite	GPS	12.18 ± 2.01
Coutts et al. (2010)[19]	79	Elite	GPS	12.9 ± 1.1
Wisbey et al. (2010)[2]	1642	Elite	GPS	13.29 ± 2.04
Aughey (2010)[72]	147	Elite	GPS	12.7 ± 1.6
Wisbey et al. (2011)[73]	1177	Elite	GPS	13.04 ± 2.01

GPS = Global Positioning System, TMA = manual Time Motion Analysis.

Total distance has been divided into three different sub-categories to provide a more comprehensive analysis of match demands including; distance per minute, distance travelled at high intensity and low intensity activity[34]. High intensity running has been categorised as movement by a player above 15 km·h^{-1} to represent an estimation of the mean ventilatory threshold of elite soccer players[61]. This provides a reference to a mean speed that is physiologically unsustainable in elite soccer players, as the majority of distance travelled is below this speed[34]. Furthermore, an enhancement of physical capacity (i.e. yo-yo IR1, yo-yo IR2 and $\dot{V}O_{2max}$) increases high intensity running during matches and simulated matches[27, 32, 38]. Recent research in soccer has focused on high intensity running due to its ability to distinguish between standards[34, 62].

Total distance and distance travelled at high intensity in an elite Australian Football pre-season match has been reported using one Hz GPS (Total distance = 9.38 km, high intensity running = 3.79 km)[15]. As players spend an uneven amount of time on the field, total distance travelled may not be the most appropriate strategy to standardise the player's physical performance. Therefore distance travelled per minute (m·min^{-1}) is more appropriate as it provides a gauge of intensity of movement and has a stronger relationship to performance[72]. For instance, distance per minute and high intensity running per minute (HIR m·min^{-1}) discriminate between regular season matches and finals matches (difference of; m·min^{-1} = 11% & HIR m·min^{-1} = 9.2%)[55]. Total match m·min^{-1} has been reported at 124 m·min^{-1} [73] and HIR m·min^{-1} at 34 m·min^{-1} [72]. Differences in m·min^{-1} across the Australian Football League (elite Australian Football competition) have gradually increased from 122 m·min^{-1} in 2008 to 124

$m \cdot min^{-1}$ in 2010[31]. Although this increase was reported to be statistically significant, an increase in approximately 1.6% is less than the noise of the GPS devices used to assess $m \cdot min^{-1}$ (CV = 3.6%). Consequently whether these results can be considered a real change is speculative and should be treated with caution by coaches and sports scientists until a more certain change is reported[6].

Some recent research has focused on using accelerometers as a measure of match exercise intensity. Accelerometer Load™ is calculated from the root sum of the squared changes in accelerations (Figure 2.3)[57]. Coe and Pivarnik investigated the validity of accelerometers to determine physical activity in youth basketball players during training sessions using heart rate monitoring[74]. Although validating accelerometer Load™ (an external output measure) with heart rate (an internal response) has its limitations in compatibility (internal vs. external training load), this study showed a moderate relationship between the two measures ($r = 0.60$)[74]. Furthermore, Montgomery et al. used accelerometer Load™ to determine the physical attributes required for different basketball drills[58]. Montgomery et al. also suggested heart rate and accelerometer Load™ may be used independently to measure physiological and physical demands of indoor sports[58]. Accelerometer Load™ possesses sufficient sensitivity to detect changes in match exercise intensity in Australian Football (noise = 1.9%, signal = 5.88%) although it is unknown if it is a valid measure of physical performance in Australian Football[57].

$$PLAYERLOAD = \sqrt{\frac{\left(a_{y1} - a_{y-1}\right)^2 + \left(a_{x1} - a_{x-1}\right)^2 + \left(a_{z1} - a_{z-1}\right)^2}{100}}$$

Where:

a_y = Forwards accelerometer
a_x = Sideways accelerometer
a_z = Vertical accelerometer
SF = Scaling factor

Figure 2.3: Calculation of accelerometer Load™ (Playerload) - Catapult Sport, Australia. As presented by Boyd et al.[57].

Positional Differences in Match Exercise Intensity

Research in soccer has investigated positional differences in match exercise intensity across 300 elite Spanish Premier League and Champions League players over 30 matches[75]. Di Salvo et al. concluded that mid-fielders travelled greater distance than defenders and forwards due to their tactical role within the team structure. Drust, Reilly and Rienzi[76] suggest the increase in total distance travelled by mid-fielders is attributed to greater low intensity activity and reveals mid-field players probably require superior aerobic power to other positions. Furthermore, defensive players are more likely to rely on anaerobic metabolism as they perform more jumps and corralling movements. These studies indicate players of different positional or tactical roles have specialised match exercise intensity profiles requiring different physical capabilities in elite soccer and thus differences are also assumed in elite Australian Football.

Australian Football requires 18 players per team to play on the field at once in 13 different specialised positions. Some of these different positions require different anthropometrical characteristics with "rucks" being the tallest and heaviest as mentioned previously[9]. Pyne et al.[9] investigated the anthropometrical and fitness status of potential draftees at the annual AFL draft camp over five consecutive years. This study found small to substantial positional differences in fitness variables such as aerobic power, agility, 20 m sprint time and vertical jump height. Furthermore, match exercise intensity, marks and possessions of AFL players vary depending on position[66]. Dawson and colleagues[66] found mid-fielders (17 km) travelled much further than full-forwards and full-backs (13.6 km). Furthermore, full-forwards and full-backs performed the greatest number of sprints per game (n = 30), whereas mid fielders performed a greater frequency of fast running per match (n = 185). These findings provide evidence that specialist-playing positions require different physical activity profiles specific to their role, which substantiates the findings of Pyne et al.[9]. Therefore playing position should be considered when analysing physical performance in Australian Football.

Fatigue in Australian Football

Monitoring fatigue in team sport is critical in monitoring the effectiveness of the athlete to utilise their physical capabilities during competition[77]. Banister[78] stipulates that physical performance equates to an athlete's physical capacity subject to their fatigue, aptly named the fitness-fatigue model. Banister's theory is widely used as a basis for periodization and athletic preparation to manipulate the interaction of fatigue and physical capacity to optimise performance (see Figure 2.4)[79, 80]. Bompa[79] suggests the length of time required to recover from a match stimulus is dependent on the strength and duration of the stimulus (i.e. training load). Both the fitness-fatigue model and supercompensation model indicate that physical performance will diminish in the presence of fatigue. In order to get a clear understanding of how performance is generated from a physical perspective it is imperative to integrate the relationship fatigue and capacity has in producing performance. The fitness-fatigue model underlines this relationship by indicating that performance is potentiated by the physical capacity yet damaged equally by fatigue[80]. Australian Football is one of the longest duration team sports in the World played over 6 months of the year therefore coaches and sports scientists have been interested in the application and detection of both acute and accumulative fatigue[19,20].

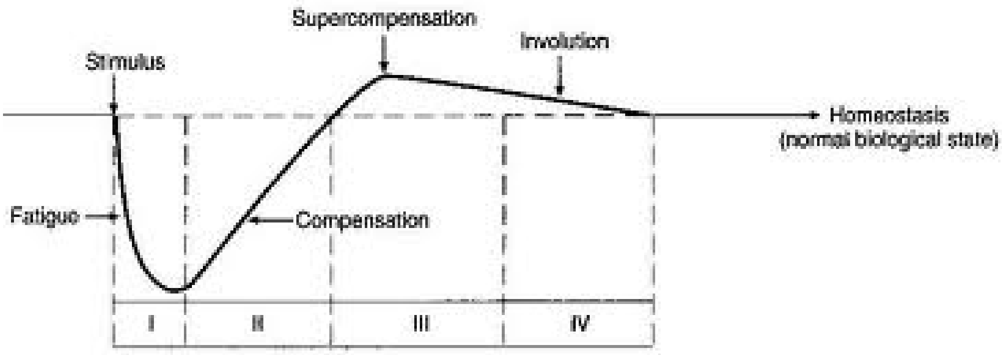


Figure 2.4: Supercompensation model as presented in Bompa (2009) pp. 15[51].

In a review of literature Noakes[23] categorised several different models of fatigue including; cardiovascular model, energy supply demand model, muscle power and recruitment model, the biomechanical model, psychological model and central governor theory. Noakes suggests all of these are accepted models of fatigue but none can fully explain reductions in performance[23]. The cardiovascular model suggests the limiting factor to exercise performance is the ability to supply enough oxygen to the operating musculature and endurance training can increase an individual's maximal rate of oxygen use, i.e. $\dot{V}O_{2max}$[23]. The energy supply demand model advocates exercise is limited by the availability of high energy substrates, i.e. ATP[23]. The muscle power and recruitment model identifies fatigue as the inability of the central nervous system to recruit required musculature[23]. The biomechanical model hypothesises fatigue is a result of the loss of movement efficiency, idealising that elastic musculature acts as a spring[23]. The psychological model suggests the athlete's performance is bound by motivation potentially at the subconscious level[23]. The central governor theory suggests exhaustive exercise performance is limited by an anticipatory feed-forward mechanism to prevent the body from catastrophic failure, i.e. myocardial ischemia[23]. Recent evidence suggests the type and severity of fatigue experienced is likely to be exercise specific[81]. Currently the role fatigue plays in Australian Football is not well known, nor the type of fatigue that affects performance. The way in which fatigue affects performance is very important to evaluate training programs and monitor athlete progression and is worthy of further investigation[20].

Evidence of Fatigue across an Australian Football Match

Australian Football is played over four playing periods (quarters) with a total length of approximately 120 minutes. It is one of the longest playing team sports in the world and consequently match exercise intensity is likely to deteriorate as fatigue progressively develops. Coutts et al.[19] investigated the trends of distance travelled across 25 elite Australian Football matches. This study found a significant decline in total distance travelled and high intensity distance from the first quarter to the final quarter (Figure 2.5). This trend of running load is supported by other research in Australian Football[2, 15]. This is also supported in other sports such as elite soccer[62] and elite rugby league[64].

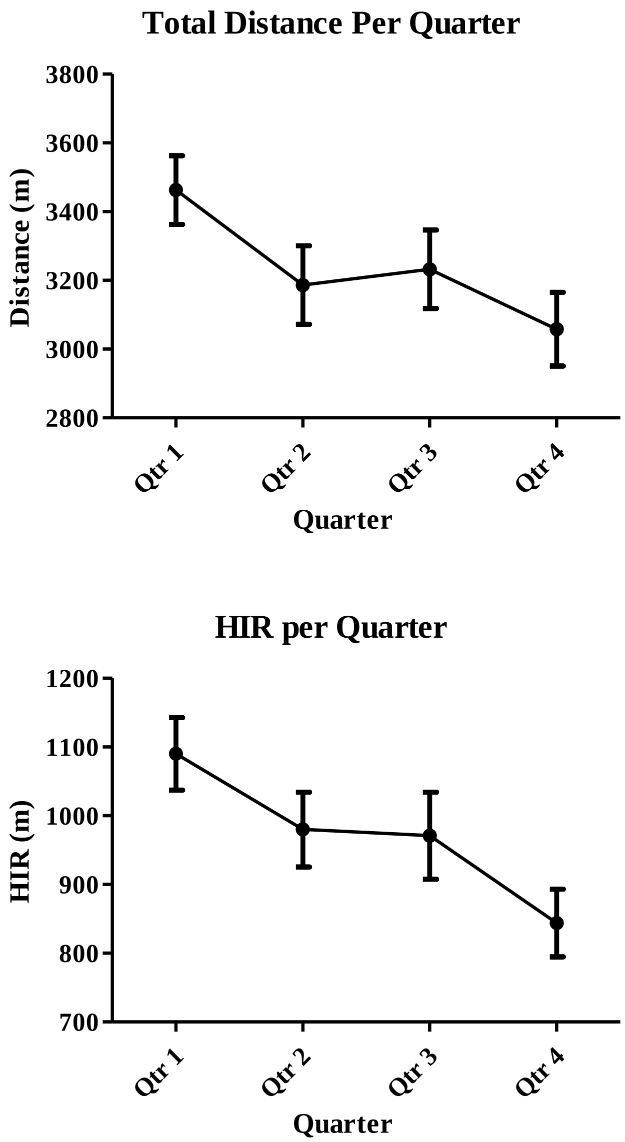


Figure 2.5: Trend of distance travelled and high intensity running (HIR) distance travelled across elite Australian Football matches. Central distribution is represented by means and 95% confidence intervals. Data extracted from Coutts et al. (2010) pp.3[19].

During an Australian Football match players are given opportunity to rest between quarters (Quarter 1 – 2 = 6 min rest; Quarter 2 – 3 = 20 min rest; Quarter 3 – 4 = 6 min rest) and within quarters through interchange at the coach's discretion. Even with these rest periods, running performance shows a decreasing trend across a match[19]. Interestingly, the mean speed of high intensity running does not decline across the match whereas the mean speed of the low intensity activity significantly declines after the first quarter[19]. Similarly, in international men's hockey during the second half, players will spend a larger percentage of time standing/walking whilst decreasing the percentage of time jogging[47]. These studies indicate players alter their activity profiles later in matches. Although the mechanisms for altering the activity profile remain unclear, a greater physical capacity may contribute to the greater physical performance in the second half[27]. The contribution of physical capacity to the activity profile throughout the match remains unknown.

The aforementioned findings have been challenged by Aughey[72] who suggests when distance is presented as a function of time on-field only small differences in distance travelled (per minute) exist, yet the number of maximal accelerations show a moderate reduction in the second on-field rotation. One explanation offered for this discrepancy in the findings was the footballers in Aughey[72] had superior physical capacity or "fatigue resistance" as they were a more successful team (in the top 25% vs. bottom 25% of rankings). To identify if physical capacity has a relevant "fatigue sparing" effect first, physical capacity must contribute to match exercise intensity, and secondly, match exercise intensity must be related to athlete and/or team performance. Currently the impact of physical capacity on the physical activity profile of players and the subsequent influence on performance is ambiguous in Australian Football.

Fatigue and Performance in Australian Football

Fatigue clearly manifests temporarily after the intense exercise required in Australian Football[77]. In the chronic absence of adequate recovery athletes may experience non-functional overreaching or overtraining syndrome[82]. Australian Footballers generally have 6 – 8 days to recover between matches. Cormack et al.[20] found that elite Australian footballers are susceptible to non-functional overreaching midway through the competitive season as fatigue gradually accumulates, but this may be overcome with appropriate periodization and recovery strategies.

To better understand the physical demands of Australian Football, and identify signs of fatigue, the physiological responses to an Australian Football match were recently investigated[15, 69]. An acute increase in core temperature[15, 69], bLA concentration and heart rate[69] and more lasting changes in endocrine and neuromuscular function (up to 72 hours post match)[20] were observed. Of these variables, core temperature, neuromuscular and endocrine functions are the only variables correlated to performance. Rise in core temperature was correlated with first quarter high intensity running ($r = 0.72$), and fourth quarter rise in core temperature was also correlated with fourth quarter very high intensity distance travelled (>24 $km \cdot h^{-1}$) ($r = 0.70$) suggesting a link between running intensity and increases in metabolic heat production[15]. For players to maintain an optimal core body temperature a pacing strategy was adopted to maintain high intensity running whilst sacrificing low intensity movements[15]. However, more evidence is required to validate these findings as only one team was used in this case study[15].

Cormack at al.[20] investigated the effect of neuromuscular and endocrine responses on coach's perception of performance. Flight time to contraction time ratio (FT:CT) of a single counter movement jump was used to determine the degree of neuromuscular fatigue, whilst salivary cortisol and testosterone concentration ratio were used to determine catabolism/anabolism status. Neuromuscular fatigue had a practically important correlation with coach's perception of performance when neuromuscular fatigue was offset by 1 week ($r = 0.24$), however, only a small correlation was found between cortisol and coach's perception of performance (r = -0.16). Interestingly, this study did not measure the impact of neuromuscular fatigue on match exercise intensity or the combined influence of physical capacity and neuromuscular fatigue on performance. These findings highlight following the questions: what are the mechanisms for the relationship found in this study? Is neuromuscular fatigue involved in limiting the athletes' ability to successfully utilise their physical capacity in order to perform optimally? The answers to these questions will have a profound effect on athlete monitoring processes and allow coaches to optimise training time.

Australian Football Performance

Defining Performance

Australian Football performance, like other team sports, is a complex phenomenon and can be categorised as outputs (measurements of team success) and inputs (contributions from individual players and contributions of specific actions or skills)[83]. To perform optimally, Smith[84] identifies athlete physiology, biomechanics, psychology, tactics and health/life style as factors affecting the athlete's ability to perform in a holistic model. Impellizzeri and Marcora[21] further categorise team sport performance in a simple model and identifies tactical, technical and physical performance as the main contributors to team success (see Figure 1.1). This team sport performance model is presented as a conceptual model of how coaches and sports scientist idealise performance in team sport. What isn't clear from this model is the way that tactical, technical and physical performance interacts with each other in a much more dynamic system.

Tactical

Tactical performance is the ability to interact with other players on the field[21]. Tactics have a close interrelationship with physical performance as different positions require different physical demands[9, 66]. It is very difficult to isolate tactical performance in an objective method, and tactical proficiency is often a subjective opinion of expert coaches. Coaches ultimately prescribe the game style to the players and provide instruction and feedback in an attempt to reinforce or alter tactical behaviours[85]. Therefore, researchers of Australian Football performance have previously used coaches rating technique (coaches' perception of performance), whereby, coaches rate each players "performance"[83]. However, limitations of this technique are: coaches' perception of performance may encompass aspects of tactical, technical and physical performance and may be biased toward the result of the match making it difficult to isolate tactical performance.

Recently more contemporary methods have been developed to identify elements of tactical performance such as pattern recognition analysis specifically the dynamic systems theory[86, 87]. Dynamic systems theory suggests that patterns can emerge in complex systems within team sport play that are critical to team success[87]. Furthermore, analysis into the interaction of the central distribution (centroid) and surface area of the team formation in small sided soccer games has been analysed to identify if patterns exist in goal scoring[88]. Francken et al. identified that in their small sided game 19 goals were scored, ten of which were scored when the centroids of both teams crossed. Although this is just over 50% of the sampled goals contextually not all goals are scored from team interactions or set-plays. This study may have found better relationships with scoring opportunities rather than scoring outcomes.

Analysing the dynamic system and central distribution in a team sport setting takes specialist tracking technology not yet employed in Australian Football.

Tactical performance is clearly an important component to winning a football match[62]. However, its relative contribution is difficult to isolate and quantify[90]. A study in elite soccer reported more goals would be scored against a team with an unbalanced defence (more attackers than defenders) (21.8%), furthermore a significant amount of goals eventuated from counter attacks (13.4%)[90]. This study suggests tactical components of the match are important to scoring opportunities in soccer. However, it is still unclear if a quantitative measure of tactical performance can be derived from observations such as Tenga et al.'s[89] study in a more holistic approach by incorporating all elements of tactical performance. Coaches' perception of performance remains the most economical choice when evaluating tactical performance because coaches' perception of performance is quick, easy, encompasses elements of tactical performance and is the most ecologically valid measure of performance[90].

To date, Australian Football research has relied on coach's perception of performance. Heasman et al.[90] found a significant correlation (r = 0.64) with coaches' votes and match outcome. This study quantified coaches' votes for each player using a subjective rating of the head coach and a well circulated newspaper on a 0 – 10 scale. This study revealed subjective expert perception of performance is a significant indicator of match outcome and thus is a valid measure of performance. Cormack et al.[20] investigated the role of endocrine and neuromuscular function on coaches perception of performance across an AFL season using coaches' votes. The votes were obtained as the sum of five coaches ratings on a 0 – 5 scale with a total possible score of 25. This study showed both neuromuscular function and salivary cortisol had small relationships with coach's votes; suggesting Australian Football performance is also affected by residual fatigue. The mechanisms of these relationships are unclear. The fitness fatigue model postulates that the fatiguing agents resulting in reduced neuromuscular function and higher salivary cortisol levels would mitigate the ability of the footballer to utilise capacity[78]. The inability for the player to utilise their capacity in this case may affect the way in which the player performs, which is identified negatively by the coaches.

Particular tactical elements, such as playing position and interchange strategy, have been proposed to influence physical performance[64, 83]. Currently Australian Football coaches have no restrictions on the number of interchange rotations they can perform during a match, allowing for frequent rest periods for their players. Coaches have been progressively increasing the rate of interchange rotations in order to delay the on-set of fatigue or to allow for greater passive recovery than would be able on the field (unpublished observations). This has been identified as a tactical advantage yet there are no studies identifying the effects of frequent rest periods on physical performance or technical performance in Australian Football.

Technical

Technical performance has previously been evaluated in soccer by the number of skill executions[62]. Notational analysis is a technique used to assess technical performance by coding specific activities during match play, i.e. the number of ball disposals. Several sports have investigated technical performance through notational analysis such as soccer [62], rugby league[64], rugby union[65], basketball[91] and tennis[92]. Rampinini et al. performed a classic study investigating the link between technical performance and physical performance with special reference to fatigue in elite soccer[62]. This study identified that the more successful teams had greater involvements with the ball and more successful passes than there less successful counterparts. Similarly, Sirotic et al. found a difference in the amount of support runs completed between elite and sub-elite rugby league matches (0.12 per minute, $p < 0.05$)[64]. Such data conceptually suggests that, technical components that contribute to match outcomes are dependent on the skill demands of the sport and the match context.

Appleby and Dawson[93] performed notational analysis on one AFL club to describe the number and outcome of skill executions such as kick-ins, marking opportunities and ruck contests. This study concluded that skill executions in isolation do not directly influence the outcome of a match. However, the authors conceded there are potential indirect effects. Dawson et al.[66] further analysed positional differences in technical performance and identified some positions require specialist skills. For example "rucks" have a greater emphasis on hit outs and marks than midfield players. Furthermore, playing position affects the frequency of match activities, as full forwards are involved in play every 112 s compared to rucks that were involved every 45 s. Although rucks are involved in the play most frequently this is not necessarily proportional to the impact they have on a match. Both Dawson et al.[66] and Appleby and Dawson's[93] work elucidate the interaction of skill execution within the context of the match is more likely to influence the result rather than purely the volume of ball interactions. One example of this is a turn-over in defence that could have a disproportionate influence on a match depending on the time in the match and how close the score was[90]. Similar findings have been found in soccer, where more successful teams (ranked in top 5) had on mean difference of 7 and 13.3 more ball involvements than less successful teams (ranked 15th – 20th) accompanied with a difference of 5.9 and 11.3 more effective short passes in the Italian Serie A league[62]. This suggests not only did the more successful team have possession of the ball more often, but they were more effective with the ball.

To put skill execution into context Heasman et al.[90] developed an impact rating to identify technical performance. This was based on skill efficiency, whereby, successful execution of a skill attracts a positive rating and an unsuccessful execution attracts a negative rating[90]. This method also ranked the skills based on a subjective impact on the match accounting for the timing of the execution, for example a successful kick for goal would be awarded more points than a handball, and more points would be awarded if the goal was scored late in the quarter (after the 20 minute mark). This method significantly correlated with winning and final margin ($r = -0.69$, 0.85, $p < 0.01$ respectively). Mid-field players had significantly more rating points than forwards and backs indicating that mid-field players have a greater impact on the match. Furthermore, Heasman et al. findings[90] highlight that possession number and more importantly, the possessions efficiency, impact match outcome. This study was the first in elite Australian Football to identify that skill execution effectiveness and skill possession number has a direct influence on match outcome. This highlights that the context with which possessions are gained is likely to be more important than simply gaining more possessions. For example, a team with a moderate number of possessions may still defeat a team with a high number of possessions if they are substantially more effective.

Physical Performance

Physical performance refers to the ability to perform sports specific movements[21]. Match exercise intensity if often used to evaluate physical performance in team sport[21]. Although very little research has been conducted in Australian Football on the influence of physical performance on match outcome, some research has been conducted in soccer. A landmark study by Rampinini et al.[62] found more successful teams (top 5 teams) in Italian Series A league covered less total distance, high intensity and very high intensity distance than their less successful counterparts (5 lowest ranked teams) (mean difference: distance = 11647 vs. 12190 m, high intensity running = 3787 vs. 4263 m & very high intensity running = 1196 vs. 1309 m respectively), yet travelled more distance with the ball (mean = 540 vs. 443 m respectively). Rampinini et al.[62] proposed the better team players are more efficient with their movements described in a complex interaction between physical performance, decision making and technical skills. The finding has identified better standards of competition have a greater yo-yo IR2[32], and yo-yo IR2 performance enables players to travel a greater distance at high intensity during peak intensity periods of the match[3]. Furthermore, another study in elite soccer found that only 1.7 ± 0.7% of distance covered (191.0 ± 80.3 m) is with the ball at a distance of 4.0 ± 1.9 m per action[94]. Physical performance is clearly a contributing factor to soccer performance but the relative contribution remains unclear. In light of the current findings, one possible explanation is that the more successful teams are more efficient with their movement than less successful teams (particularly when players do not have the ball), or control the tempo of the match.

Wisbey et al.[7] introduced an "exertion index" to evaluate match exercise intensity in Australian Football. This was described as a unit of exertion based on a theoretical polynomial relationship between speed and energy cost, which has a large correlation with total distance travelled (r = 0.95). This report found a large relationship between mean exertion index and final ladder position in the AFL (r = 0.85). However, this measure could not predict the outcome of a match with teams having the larger exertion index only winning 49% of the time. Furthermore, total disposals was moderately correlated with distance travelled (r = 0.34), indicating that travelling a greater distance creates greater opportunities to gain possessions in elite Australian Football. However, the reports of Wisbey et al.[7] did not investigate the relationships between any currently established reliable measures of match exercise intensity (physical performance) and other forms of performance (tactical and technical). This information would allow coaches and sport scientists to determine the impact of match exercise intensity on individual and team performance, thus should be investigated further. To date there is a dearth of knowledge regarding the influence of physical performance on overall Australian Football performance.

Conclusion

Current time motion analysis research into elite Australian Football has highlighted similarities in total distance to elite soccer yet much greater than elite rugby league and union. Although the locomotion demands are similar the tactical and technical demands are much different between the codes. Findings into the relevance into match activity profile of soccer players have shown team success may not be as simple as running a greater distance. Players require a greater physical capacity in higher levels of competition to be able to perform at a high intensity yet, travelling greater distances within matches is not advantageous. The research has also revealed the specific relevance of match exercise intensity toward overall performance is unknown. This presents challenges to the coach when designing training programs, designing load management systems and implementing tactical strategies such as resting players.

Conceptually the literature indicates that Australian Football performance is multi-factorial comprising of three categories of performance: tactical, technical and physical. Physical performance in particular demonstrates malleability through training and rest periods whist tactical and technical performance is contextually driven with in a match. It is currently unclear whether physical, tactical and technical performances are interrelated or independent in Australian Football or how we can positively manipulate components of these performance measures. Future studies should therefore focus on identifying the effect of match exercise intensity on tactical and technical performance, as well as investigating the potential means of improving performance through influential factors such as fatigue.

References

1. Jaques TD, Pavia GR. An analysis of the movement patterns of players in an Australian Rules league football match. The Australian Journal of Sports Medicine. 1974;5(10):10-20.
2. Wisbey B, Rattray B, Pyne DB. Quantifying changers in AFL demands using GPS tracking 2009 AFL season. Canberra, Australia: FitSense Australia2010 Contract No.5: Report.
3. Bangsbo J, Iaia FM, Krustrup P. The yo-yo intermittent recovery test: A useful tool for evaluation of physical performance in intermittent sports. Sports Medicine. 2008;38(1):37-51.
4. Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. Journal of Science and Medicine in Sport. 2010;13(1):133-5.
5. Di Salvo V, Collins A, McNeill B, Marco C. Validation of Prozone: A new video-based performance analysis system. Journal of Performance Analysis in Sport. 2006;6(1):108-18.
6. Jennings D, Cormack S, Coutts AJ, Boyd L, Aughey RJ. The validity and reliability of GPS units for measuring distance in team sport specific running patterns. International Journal of Sports Physiology and Performance. 2010;5(3):328-41.
7. Wisbey B, Rattray B, Pyne DB. Quantifying changes in AFL player game demands using GPS tracking 2008 AFL season. Canberra, Australia: FitSence Australia 2009 Contract No.4: Report.
8. Gray AJ, Jenkins DG. Match analysis and the physiological demands of Australian football. Sports Medicine. 2010;40(4):347-60.

9. Pyne DB, Gardner AS, Sheehan K, Hopkins WG. Positional differences in fitness and anthropometric characteristics in Australian football. Journal of Science and Medicine in Sport. 2006;9(1-2):143-50.

10. Norton KI, Craig NP, Olds TS. The evolution of Australian football. Journal of Science and Medicine in Sport. 1999;2(4):389-404.

11. Pyne DB, Gardner AS, Sheehan K, Hopkins WG. Fitness testing and career progression in AFL football. Journal of Science and Medicine in Sport. 2005;8(3):321-32.

12. Young W, Newton RU, Doyle TL, Chapman D, Cormack S, Stewart G, et al. Physiological and anthropometric characteristics of starters versus non-starters and playing position in elite Australian Football: A case study. Journal of Science and Medicine in Sport. 2005;8(3):333-45.

13. Thomas A, Dawson B, Goodman C. The yo-yo test: reliability and association with a 20-m shuttle run and VO(2max). International Journal of Sports Physiology and Performance. 2006;1(2):137-49.

14. Young W, Prior L. Relationship between pre-season anthropometric and fitness measures and indicators of playing performance in elite junior Australian Rules football. Journal of Science and Medicine in Sport. 2007;10:110-8.

15. Duffield R, Coutts A, Quinn J. Core temperature responses and match running performance during intermittent sprint condition in warm conditions. Journal of Strength and Conditioning Research. 2009;23(4):1238-44.

16. Lorenzen C, Williams MD, Turk PS, Meehan DL, Kolsky DJ. Relationship between velocity reached at VO2(max) and time-trial performances in elite

Australian Rules footballers. International Journal of Sports Physiology and Performance. 2009;4(3):408-11.

17. Hunter JR, O'Brien B J, Mooney MG, Berry J, Young WB, Down N. Repeated Sprint Training Improves Intermittent Peak Running Speed in Team-Sport Athletes. Journal of Strength and Conditioning Research. 2011;25(5):1318-25.

18. Mooney MG, Hunter JR, O'Brien B J, Berry JT, Young WB. Reliability and Validity of a Novel Intermittent Peak Running Speed Test for Australian Football. Journal of Strength and Conditioning Research. 2011;25(4):966-79.

19. Coutts AJ, Quinn J, Hocking J, Castagna C, Rampinini E. Match running performance in elite Australian Rules Football. Journal of Science and Medicine in Sport. 2010;13(5):543-8.

20. Cormack SJ, Newton RU, McGuigan MR, Cormie P. Neuromuscular and endocrine responses of elite players during an Australian rules football season. International Journal of Sports Physiology and Performance. 2008;3(4):439-53.

21. Impellizzeri FM, Marcora SM. Test validation in sport physiology: Lessons learned from clinimetrics. International Journal of Sports Physiology and Performance. 2009;4:269-77.

22. McArdle WD, Katch FI, Katch VL. Exercise physiology: Energy, nutrition, and human performance. Darcy P, editor. Philadelphia, Pennsylvania: Lippincott Williams & Wilkins; 2001.

23. Noakes. Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. Scandinavian Journal of Medicine Science in Sports. 2000;10(3):123.

24. Wyatt FB, Swaminathan A. Implementing a mathematical model to compare oxygen uptake kinetics between cyclists and noncyclists during steady state. Journal of Strength and Conditioning Research. 2010;24(10):2627-31.

25. Grant JA, Joseph AN, Campagna C. The Prediction of VO_{2max}: A Comparison of 7 Indirect Tests of Aerobic Power. Journal of Strength and Condititioning Research. 1999;13(4):347-52.

26. Rampinini E, Sassi A, Azzalin A, Castagna C, Menaspa P, Carlomagno D, et al. Physiological determinants of Yo-Yo intermittent recovery tests in male soccer players. European Journal of Applied Physiology. 2010;108(2):401-9.

27. Helgerud J, Engen LC, Wisloff U, Hoff J. Aerobic endurance training improves soccer performance. Medicine & Science in Sports & Exercise. 2001;33(11):1925-31.

28. McNicol AJ, O'Brien BJ, Paton CD, Knez WL. The effects of increased absolute training intensity on adaptations to endurance exercise training. Journal of Science and Medicine in Sport. 2009;12(4):485-9.

29. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. Sports Medicine. 2004;34(7):465-85.

30. Stratton E, O'Brien BJ, Harvey J, Blitvich J, McNicol AJ, Janissen D, et al. Treadmill Velocity Best Predicts 5000-m Run Performance. International Journal of Sports Medicine. 2009;30(1):40-5.

31. Wisbey B, Montgomery P, Pyne DB, Rattray B. Quantifying movement demands of AFL football using GPS tracking. Journal of Science and Medicine in Sport. 2010;13(5):531-6.

32. Krustrup P, Mohr M, Amstrup T, Rysgaard T, Johansen J, Steensberg A, et al. The yo-yo intermittent recovery test: Physiological response, reliability, and validity. Medicine & Science in Sports & Exercise. 2003;35(4):697-705.

33. Hopkins WG. Measures of reliability in sports medicine and science. Sports Medicine. 2000;30(1):1-15..

34. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. Journal of Sports Sciences. 2003;21:519-28.

35. Glaister M. Multiple sprint work: Physiological responses, mechanisms of fatigue and the influences of aerobic fitness. Sports Medicine. 2005;35(9):757-77.

36. Spencer M, Bishop D, Dawson B, Goodman C. Physiological and metabolic responses of repeated-sprint activities:specific to field-based team sports. Sports Medicine. 2005;35(12):1025-44.

37. Spencer M, Fitzsimons M, Dawson B, Bishop D, Goodman C. Reliability of a repeated sprint test for field-hockey. Journal of Science and Medicine in Sport. 2006;9:181-4.

38. Rampinini E, Bishop D, Marcora SM, Ferrari Bravo D, Sassi R, Impellizzeri FM. Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. Interational Journal of Sports Medicine. 2007;28(3):228-35.

39. Dawson B, Fitzsimons M, Ward D. The relationship of repeated sprint ability to aerobic power and performance measures of anaerobic work capacity and power. The Australian Journal of Science and Medicine in Sport. 1993;25(4):88-93.

40. Trump ME, Heigenhauser GJF, Putman CT, Spriet LL. Importance of muscle phosphocreatine during intermittent maximal cycling. Journal of Applied Physiology. 1996;80(5):1574-80.

41. Serpiello FR, McKenna MJ, Stepto NK, Bishop DJ, Aughey RJ. Performance and physiological responses to repeated-sprint exercise: a novel multiple-set approach. European Journal of Applied Physiology. 2011;111(4):669-78.

42. Moore A, Murphy A. Development of an anaerobic capacity test for field sport athletes. Journal of Science of Medicine in Sport. 2003;6(3):275-84.

43. Medbo JI, Mohn AC, Tabata I, Bahr R, Vaage O, Sejersted OM. Anaerobic capacity determined by maximal accumulated O2 deficit. Journal Applied Physiology. 1988;64(1):50-60.

44. Bangsbo J, Gollnick PD, Graham TE, Juel C, Kiens B, Mizuno M, et al. Anaerobic energy production and O2 deficit-debt relationship during exhaustive exercise in humans. Journal of Physiology. 1990;422:539-59.

45. Renoux JC, Petit B, Billat V, Koralsztein JP. Oxygen deficit is related to the exercise time to exhaustion at maximal aerobic speed in middle distance runners. Archives of Physiology and Biochemisty. 1999;107(4):280-5.

46. Reilly T, Thomas V. A motion analysis of work rate in different positional roles in professional football match play. Journal of Human Movement Studies. 1976;2:87-97.

47. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, Goodman C. Time motion analysis of elite field hockey, with special reference to repeated sprint ability. Journal of Sports Sciences. 2004;22(9):843-50.

48. Withers RT, Maricic Z, Wasilewski S, Kelly L. Match analyses of Australian professional soccer players. Journal of Human Movement Studies. 1982;8:159-76.

49. Mayhew SR, Wenger HA. Time motion analysis of professional soccer. Journal of Human Movement Studies. 1985;11:49-52.

50. Bangsbo J, Norregaard L, Thorso F. Activity profile of competition soccer. Canadian Journal of Sport Science. 1991;16(2):110-6.

51. Dobson BP, Keogh JW. Methodological issues for the application of time-motion analysis research. Strength and Conditioning Journal. 2007;29(2):48-55.

52. Larsson P. Global positioning system and sport-specific testing. Sports Medicine. 2003;33(15):1093-101.

53. Castellano J, Casamichana D, Calleja-González J, San Román J, Ostojic SM. Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. Journal of Sports Science and Medicine. [Letter to the Editor]. 2011;10:233-4.

54. Duffield R, Reid M, Baker J, Spratford W. Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. Journal of Science in Medicine Sport. 2010;13(5):523-5.

55. Aughey RJ. Increased high intensity activity in elite Australian football finals matches. International Journal of Sports Physiology and Performance. 2011;6(3):367-79.

56. Randers MB, Mujika I, Hewitt A, Santisteban J, Bischoff R, Solano R, et al. Application of four different football match analysis systems: A comparative study. Journal of Sports Sciences. 2010:28(2) 171-82.

57. Boyd L, Ball K, Aughey RJ. The reliability of minimaxX accelerometers for measuring physical activity in Australian football. International Journal of Sports Physiology and Performance. 2011;6(3):311-21.

58. Montgomery PG, Pyne DB, Minahan CL. The physical and physiological demands of basketball training and competition. Internationnal Journal of Sports Physiology and Performance. 2010;5(1):75-86.

59. Ruch N, Rumo M, Mader U. Recognition of activities in children by two uniaxial accelerometers in free-living conditions. European Journal of Applied Physiology. 2011;111(8):1917-27.

60. Wixted AJ, Billing DC, James DA. Validation of trunk mounted inertial sensors for analysing running biomechanics under field conditions, using synchronously collected foot contact data. Sports Engineering. 2010;12(4):207-12.

61. Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. High intensity running in English FA Premier League soccer matches. Journal of Sports Sciences. 2009;27(2):159-68.

62. Rampinini E, Impellizzeri FM, Castagna C, Coutts A, Wisloff U. Technical performance during soccer matches of the Italian Sere A league: Effect of fatigue and competitive level. Journal of Science and Medicine in Sport. 2009;12(1):227-33.

63. King T, Jenkins D, Gabbett T. A time-motion analysis of professional rugby league match-play. Journal of Sports Sciences. 2009;27(3):213-9.

64. Sirotic AC, Coutts A, Knowles H, Catterick C. A comparison of match demands between elite and semi-elite rugby league competition. Journal of Sports Sciences. 2009;27(3):203-11.

65. Roberts SP, Trewartha G, Higgitt RJ, El-Abd J, Stokes KA. The physical demands of elite English rugby union. Journal of Sports Sciences. 2008;26(8):825-33.

66. Dawson B, Hopkinson R, Appleby B, Stewart G, Roberts C. Player movement patterns and game activities in the Australian Football league. Journal of Science and Medicine in Sport. 2004;7(3):278-91.

67. Wisbey B, Montgomery P. Quantifying AFL player game demands using GPS tracking. Canberra, Australia: FitSence Australia2006 Contract No.2: Report.

68. Veale JP, Pearce AJ, Carlson JS. Player movement patterns in an elite junior Australian Rules football team: An exploratory study. Journal of Sports Science and Medicine. 2007;6:254-60.

69. Veale JP, Pearce AJ. Physiological responses of elite junior Australian rules footballers during match play. Journal of Sports Science and Medicine. 2009;8:314-9.

70. Wisbey B, Montgomery P. Quantifying changes in AFL player game demands using GPS tracking. Canberra, Australia: FitSence Australia 2007 Contract No.3: Report.

71. Wisbey B, Montgomery P, Pyne DB. Quantifying changes in AFL player game demands using GPS tracking. Canberra, Australia: FitSence Australia 2008 Contract No.4: Report.

72. Aughey RJ. Australian football player work rate: evidence of fatigue and pacing? International Journal of Sports Physiology and Performance. 2010;5(3):394-405.

73. Wisbey B, Rattray B, Pyne DB. Quantifying changes in AFL player game demands using GPS tracking 2008 AFL season. Canberra, Australia: FitSence Australia2009 Contract No.5: Report.

74. Coe D, Pivarnik JM. Validation of the CSA accelerometer in adolescent boys during basketball practice. Pediatric Exercise Science. 2001;13(4):373-9.

75. Di Salvo V, Baron R, Tschan H, Calderon Montreo FJ, Bachl N, Pigozzi F. Performance characteristics according to playing position in elite soccer. Internation Journal of Sports Medicine. 2007;28:222-7.

76. Drust B, Reilly T, Rienzi E. Analysis of work rate in soccer. Sports Exercise and Injury. 1998;4:151-5.

77. Morton RH, Fitz-Clarke JR, Banister EW. Modeling human performance in running. Journal of Applied Physiology. 1990;69(3):1171-7.

78. Banister EW. Physiological Testing of the High Performance Athlete. In: MacDougall JD, Wender HA, Gree HJ, editors. Champaign, IL: Human Kinetics; 1991. p. 403-24.

79. Bompa T. Periodization theory and methodology of training. 5th ed. Champaign, IL: Human Kinetics; 2009.

80. Chiu LZF, Barnes JL. The Fitness-Fatigue Model Revisited: Implications for Planning Short- and Long-Term Training. Strength & Conditioning Journal. 2003;25(6):42-51.

81. Duffield R, Murphy A, Snape A, Minett GM, Skein M. Post-match changes in neuromuscular function and the relationship to match demands in amateur rugby league matches. Journal of Science and Medicine Sport. 2011 (In Press).

82. Meeusen R, Duclos M, Gleeson M, Rietjens G, Steinacker J, Urhausen A. Prevention, diagnosis and treatment of the Overtraining Syndrome. European Journal of Sport Science. 2006;6:1-14.

83. Carmichael F, Thomas D, Ward R. Team performance: The case of English Premier football. Managerial and Decision Economics. 2000;21:31-45.

84. Smith DJ. A framework for understanding the training process leading to elite performance. Sports Medicine. 2003;33(15):1103-26.

85. Renshaw I, Davids KW, Shuttleworth R, Chow JY. Insights from ecological psychology and dynamical systems theory can underpin a philosophy of coaching. International Journal of Sport Psychology. 2009;40(4):540-602.

86. Grehaigne J-F, Bouthier D, David B. Dynamic-system analysis of opponent relationships in collective actions in soccer. Journal of Sports Sciences. 1997;15(2):137-49.

87. Reed D, Hughes M. An Exploration of Team Sport as a Dynamical System. International Journal of Performance Analysis in Sport. 2006;6(2):114-25.

88. Frencken W, Lemmink K, Delleman N, Visscher C. Oscillations of centroid position and surface area of soccer teams in small-sided games. European Journal of Sport Science. 2011;11(4):215-23.

89. Tenga A, Holme I, Tore Ronglan L, Bahr R. Effect of playing tactics on goal scoring in Norwegian professional soccer. Journal of Sports Sciences. 2010;28(3):237-44.

90. Heasman J, Dawson B, Berry J, Stewart G. Development and validation of a player impact ranking system in Australian football. International Journal of Performance Analysis in Sport. 2008;8(3):56-171.

91. Miller S, Bartlett R. The relationship between basketball shooting kinematics, distance and playing position. Journal of Sports Sciences. 1996;14(3):243-53.

92. Gillet E, Leroy D, Thouvarecq R, Stein JF. A notational analysis of elite tennis serve and serve-return strategies on slow surface. Journal of Strength and Conditioning Research. 2009;23(2):532-9.

93. Appleby B, Dawson B. Video anallysis of selected game activities in Australian Rules football. Journal of Science and Medicine in Sport. 2004;5(2):129-42.

94. Carling C. Analysis of physical activity profiles when running with the ball in a professional soccer team. Journal of Sports Science. 2010;28(3):319-26.

Chapter 3: The relationship between physical capacity and match performance in an elite Australian Football team: A mediation approach

Abstract

Objective: The aim of this study was to verify if the yo-yo intermittent recovery test (level 2) (yo-yo IR2) score is linked to Australian Football performance through match exercise intensity.

Method: Twenty-one data sets were recorded from nine individual players that completed the yo-yo IR2, and played an Australian Football League match in the first five rounds of the 2010 season wearing a global positioning system (GPS) unit. Simple mediation modelling was used to analyse the inter-relationship between yo-yo IR2 score, match exercise intensity and Australian Football performance. Playing position and experience were also incorporated into the model to identify conditional affects.

Results: A significant direct relationship was observed between yo-yo IR2 and number of ball disposals ($p < 0.1$) and a significant indirect relationship was observed between yo-yo IR2 and number of ball disposals through distance travelled at high intensity (HIR $m \cdot min^{-1}$) ($p < 0.1$). Moderation analysis showed that playing position affected the relationship between of yo-yo IR2 and HIR $m \cdot min^{-1}$ ($p < 0.1$) and HIR $m \cdot min^{-1}$ and total ball disposals ($p < 0.1$). Playing experience also significantly affected the relationship between HIR $m \cdot min^{-1}$ and total ball disposals.

Conclusions: This study is the first to identify the effects of yo-yo IR2 on total ball disposals through HIR $m \cdot min^{-1}$ performed during Australian Football matches and that playing position and playing experience affect these interactions.

Key Words: Global Positioning System, Yo-Yo intermittent recovery test, team sport, match exercise intensity.

Introduction

Due to advances in player tracking technology, recent studies examining the match demands of top level team sports have provided an improved understanding of the requirements of competition[1, 2]. In addition, recent studies in soccer have shown that training physical capacities (such as endurance qualities) can positively impact on match exercise intensity[3, 4]. However, at present there is little empirical knowledge about the contribution of specific physical capacities to Australian Football performance, or if match exercise intensity mediates this relationship.

In a recent conceptual model of factors affecting soccer performance, Impellizzeri and Marcora[5] suggested that tactical, technical and physical performance were relevant constructs of team ranking. It was also reported that high intensity activity (match exercise intensity) is a causal indicator of overall physical performance, and that valid field tests provide an indication of the capacity of the athlete to produce high intensity activity[5]. This model suggests that match exercise intensity may mediate the effect (i.e. act in a causal sequence between two variables)[6] of physical capacity on performance in soccer. However, further conditional circumstances (e.g. gender, age etc.) may also impact on these relationships. These variables are defined as moderators and can be incorporated into a mediation model[6]. Some studies have identified relationships, exclusively in soccer, between training adaptations and improved physical capacity, improved physical capacity and match exercise intensity, and match exercise intensity and team success[4, 7, 8]. However, a mediation analysis has not yet been conducted to determine if these relationships are linked.

Studies on soccer players have shown that improvements in aerobic endurance are matched with increased distance[8, 9] and increased involvement with the ball[8]. Gains in these qualities may also improve match exercise intensity and subsequently impact on similar performance variables in Australian Football. In support of this, several studies have shown that higher endurance qualities (i.e. maximal oxygen uptake, yo-yo IR2) and anaerobic qualities (i.e. 5 and 10 m sprint time) components are important for elite Australian Football players[10, 11]. For example, Young et al.[10] found that the yo-yo intermittent recovery (level 2) (yo-yo IR2) was significantly higher in starters compared to non-starters at the start of an Australian Football League (AFL) season. Furthermore, the yo-yo IR2 has been identified to have a strong relationship with high intensity distance travelled in soccer[3, 7]. Together, these studies show that the yo-yo IR2 is a relevant physical capacity test of high intensity intermittent endurance for team sports, suggesting the model of Impellizzeri and Marcoa[5] also applies to Australian Football. Currently, the relationships between yo-yo IR2 performance and physical and playing performance in Australian Football has not been identified.

Therefore, this study aimed to identify: 1) if there is a relationship between yo-yo IR2 score and various performance measures in Australian Football (i.e. ball disposals, player impact score and coaches' rating), 2) if match exercise intensity is a mechanism of the relationship; and, 3) if playing position and playing experience impact on these relationships.

Methods

Forty-six male elite Australian footballers from the same team were invited to participate in this study. The participants had a mean (±SD) stature of 187.6 ±7.3 cm, mass of 86.5 ±8.7 kg and age of 22.3 ±3.3 years. Informed consent was gathered prior to the commencement of the studies. Ethical approval was obtained by the University Research Ethics Committee (see Appendix A).

Physical capacity (reflected by yo-yo IR2), match exercise intensity (reflected by distance per minute, high intensity distance per minute and summation of accelerations per minute) and match performance (reflected by player impact score based on skill involvement and coaches rating of performance) measures were gathered on participants in a prospective design.

A sample was determined as the same player possessing a yo-yo IR2 score, match exercise intensity and match performance records in the first 5 matches of the season. Of the forty-six footballers invited to participate, only nine recorded at least one sample (ranging 1 – 3) due to test completion, technical error with Global Positioning System units and player selection. A total of 21 samples were obtained. This study predicates Banisters theory that performance is equal to an athlete's capacity subject to fatigue[12]. In order to isolate the impact of physical capacity on performance it was first assume that capacity will not change over the experimental period, this is supported by current literature in elite soccer[13]. Secondly, it was assume that non-functional overreaching is not occurring. As it is outside the scope of this study to measure fatigue we felt it is appropriate to delimit the study to the first 5 matches before cumulative fatigue could potentially confound the results[14].

Participants were required to perform the yo-yo IR2 less than 2 weeks prior to the first match of the regular season. All participants performed the test on the same indoor surface. Each participant had completed this test previously and was familiar with the procedures. This procedure has been described in detail elsewhere with typical errors ranging from 4.9−10.4% for a variety of sports and standards[15]. After the test, participants underwent one week of their regular training before the commencement of the season.

All participants had their match exercise intensity recorded by portable GPS sampling at 5 Hz (MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia). Match exercise intensity and performance measures were gathered for the first five matches of the season, similar to the approach of Young and Prior[16]. Global positioning system data was downloaded post match using manufacture specific software (Logan Plus v. 4.4.0, Scoresby, Australia) for analysis.

Match exercise intensity was only recorded for the on-field playing duration of each participant. In an attempt to reduce the likelihood of reporting artificially high match exercise intensities, GPS samples were only accepted for analysis if the participant played ≥70% of total match time (range 70 – 96% total match time). The exercise intensity variables collected were distance travelled per minute ($m \cdot min^{-1}$) and distance travelled at high intensity per minute (HIR $m \cdot min^{-1}$) where HIR m =distance travelled above 15 $km \cdot h^{-1}$. These variables have been tested for reliability and validity; distance CV =3.6%, validity 3.9% different from reference; high intensity distance (striding and sprinting) CV = 9.0–11.9% (activity dependent), validity range -6.2–4.6% (activity dependent)[17].

The participant's number of skill involvements (ball disposals) and player rank were collected by a commercial statistical analytics company (Champion Data©, South Bank, Australia). The Champion Data© player ranking system is based on the impact of the player upon the match. A positive rating is allocated to each effective skill execution such as: kicks, handballs, tackles, hit-outs, marks and scoring shots and negative rating is allocated for ineffective skill executions. This rank is similar to the performance measure of Heasman et al.[18] Champion Data© provide a 99% accuracy rate for match statistics[19].

Coaches' perceptions of players performance was collected according to previously described methods[20]. Briefly, five team coaches were asked to rate each participating player's performance on a 1–5 scale (1 = poor performance, to 5 = excellent performance) within an hour after the completion of the match. The sum of the five coaches' votes was used to quantify the player's subjective performance, which encompasses both tactical and technical performance. Internal consistency reliability was conducted after each match and showed a Cronbach's alpha ranging between 0.88 and 0.92 satisfying acceptable reliability (>0.8)[21].

The statistical approach utilised was mediation analysis. The yo-yo IR2 was analysed as the independent variable, while tactical and technical performance measures were individually analysed as dependant variables and match exercise intensity measures as the mediators (see Figure 3.1). Mediation analysis is a process that identifies if a third variable mediates (M = match exercise intensity) an effect between an independent variable (X = yo-yo IR2) and a dependent variable (Y = performance) in a causal sequence[22]. Preacher and Hayes[22] suggest that the causal step approach be used to identify if the variables satisfied the mediation criteria (see Figure 3.1). The causal step approach maintains that in order to satisfy a mediation relationship in the causal sequence, analysis for effects *c, a and b* must be significant, and *ć* must not be significant. Importantly, *c* is analysed by incorporating the mediator and *ć* is analysed by holding the mediator constant. Thus, if the mediator is in fact a mechanism of the relationship between X and Y, accounting for the mediating variable will weaken the relationship to a non-significant level.

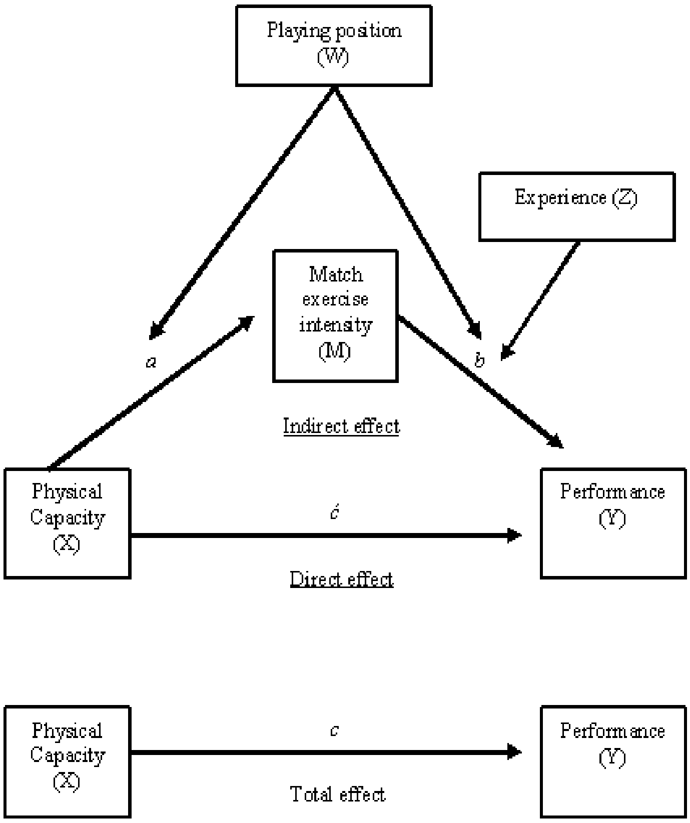


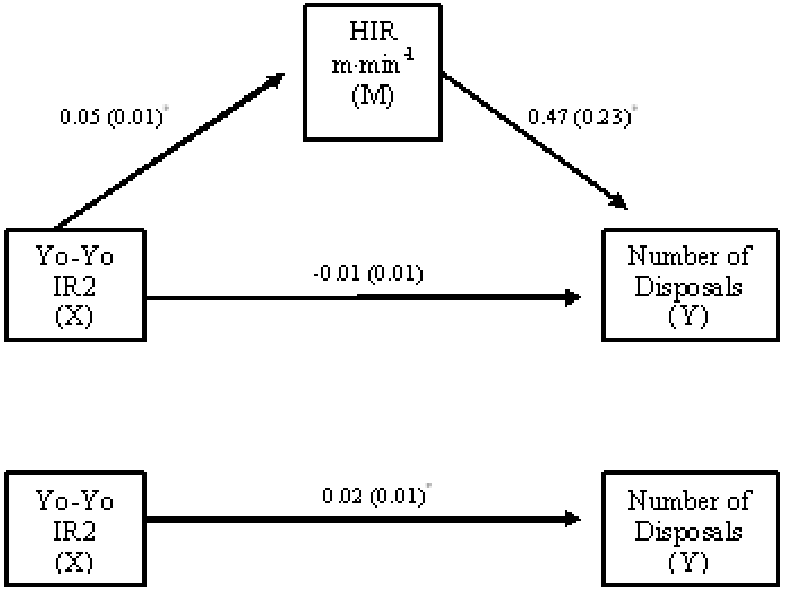
Figure 3.1: A graphical representation of the path of simple mediation analysis adapted from Preacher and Hayes, 2008 pp. 880[22]. X represents the independent variable (physical capacity), Y represents the dependent variable (performance) and M indicates the mediator (match exercise intensity), W represents a moderator for the effect of X→M and X→Y, Z represents the moderator for the effect of M→Y. The effect of X→M is represented by *a*, the effect of M→Y is represented by *b*. The total effect (*c*) of physical capacity (X) on performance (Y) is comprised of the sum of the direct effect (*ć*) and indirect effect (*ab*).

Following satisfaction of a mediation effect, the indirect effect was analysed via the bootstrap method. Bootstrapping is the process whereby a pre-determined number of random selection of the sample is obtained, each data record may be chosen multiple times or never[22]. Bootstrap selection reduced bias and likelihood of type 1 errors, in this study the bootstrap sample was set at 3000 samples[22]. The indirect effect establishes the degree to which the independent variable and mediator can explain the dependant variable in a causal sequence calculated as $c - \acute{c}$ (See Figure 3.1). Six separate single mediation analyses combinations were performed to isolate the inter-relationships between variables. Mediation was analysed using SPSS v.17 (SPSS Inc., Chicago, USA) using macro and syntax from Preacher and Hayes[22], with significance set at p value of <0.1 as suggested by Batterham and Hopkins[23]. Mediation analysis assumes normality for between variable analyses, therefore all data was deemed normally distributed by a Kolmogorov-Smirnov test before being included into the mediation analysis.

Once a mediation relationship was identified, mediation analysis was repeated under conditional variables (moderators) to ascertain if the relationships were influenced by playing position and/or playing experience. Playing position (W) was separated into two categories of key position (centre half back/forward and full forward/back) and non-key position players (forward/back pockets, half forward/back flanks, wings and midfielders) and was included as a moderator for effects *a* and *b*. Playing experience (Z) was separated into two categories, above and below 50 AFL matches, and was included as a moderator of only effect *b*, as the relationship between yo-yo IR2 and match exercise intensity should not be influenced by experience in elite Australian Football (see Figure 3.1). Mediation-Moderation effect was analysed in SPSS v.17 (SPSS Inc., Chicago, USA) using macro and syntax from Preacher, Rucker and Hayes (moderation-mediation)[24], with a <0.1 significance level.

Results

The mean physical capacity measured by yo-yo IR2 was 1060 ±176 m and match exercise intensity measured by $m \cdot min^{-1}$ and HIR $m \cdot min^{-1}$ was 139.0 ±11.1 m and 40.6 ±9.6 m respectively. Of the six mediation combinations that were tested (1 independent variable, 3 mediators and 3 dependant variables), five failed to meet causal step approach mediation criteria. Significant relationships were found between yo-yo IR2 and all match exercise intensity measures. However, only yo-yo IR2 and total ball disposals showed a significant relationship that was mediated by HIR $m \cdot min^{-1}$ (Figure 3.2). The strength of the mediation indicates that 15.4% of the variation in total ball disposals can be attributed to the indirect effect of yo-yo IR2 and HIR $m \cdot min^{-1}$ (Figure 3.2). Figure 3.2 shows a positive effect of yo-yo IR2 on HIR $m \cdot min^{-1}$ and a positive effect of HIR $m \cdot min^{-1}$ on number of ball disposals independent of yo-yo IR2.



Independent Variable (X)	Mediator (M)	Dependent Variable (Y)	N	Bootstrap sample	Indirect Effect	R^2	P value
Yo-yo IR2	m·min^{-1}	Total Disposals	21	3000	0.01 ± 0.01	15.4%	0.44
Yo-yo IR2	m·min^{-1}	Champion Data Rank	21	3000	-0.02 ± 0.04	0%	0.58
Yo-yo IR2	m·min^{-1}	Coaches Rating	21	3000	-.003 ± 0.01	13.9%	0.7
Yo-yo IR2	HIR m·min^{-1}	Total Disposals	21	3000	0.02 ± 0.01	15.4%	0.06
Yo-yo IR2	HIR m·min^{-1}	Champion Data Rank	21	3000	0.018 ± 0.047	2.9%	0.7
Yo-yo IR2	HIR m·min^{-1}	Coaches Rating	21	3000	0.001 ± 0.008	25.1%	0.98

Figure 3.2: Mediation model showing the effects between variables. Units are presented as standardised regression coefficients and the standard errors are in parentheses. A summary of the indirect effect ± standard errors of the combinations through bootstrap technique is also shown. Asterix represents significance at the 0.1 level.

Adding playing position as a moderator to the above mediation model revealed that non-key position players strengthened the indirect effect by improving the relationship between yo-yo IR2 and HIR $m \cdot min^{-1}$ (indirect effect = 0.023 ±0.011, $p = 0.04$), and HIR $m \cdot min^{-1}$ and number of ball disposals (indirect effect = 0.022 ±0.011, $p = 0.04$). Furthermore, incorporating playing experience as a moderator strengthened the indirect relationship between yo-yo IR2 and ball disposals in the >50 match experience cohort (indirect effect = 0.024 ±0.012, $p = 0.04$).

Discussion

This study aimed to identify a relationship between a physical capacity measure (yo-yo IR2) and Australian Football performance. The results showed that yo-yo IR2 is correlated with number of ball disposals and is mediated by HIR $m \cdot min^{-1}$. These results present a succinct and novel model of the contribution of physical capacity to Australian Football performance. Noteworthy components of this model include: a) the total effect of yo-yo IR2 score to number of ball disposals; b) the effect yo-yo IR2 has on HIR $m \cdot min^{-1}$; c) the effect of HIR $m \cdot min^{-1}$ on the number of ball disposals for a given yo-yo IR2 score; and d) the indirect effect of yo-yo IR2 and HIR $m \cdot min^{-1}$ on the number of ball disposals. Whilst relationships between physical capacities and performance have been observed in golf[25] and soccer[8], the present findings are the first to show an indirect effect of a physical capacity measure and Australian Football performance through a mediator (match exercise intensity). The magnitude of the indirect effect indicates that 15.4% of the variation in the number of ball disposals can be attributed to the indirect influence of yo-yo IR2 and HIR $m \cdot min^{-1}$.

A notable finding from this study was that of all the combinations analysed, yo-yo IR2, HIR m·min^{-1} and number of ball disposals was the only combination to satisfy the mediation criteria. This shows that HIR m·min^{-1} is an important physical performance variable to increase when attempting to improve disposal count. Moreover, the present findings suggest that this can be achieved by improving yo-yo IR2 score. The relationship between yo-yo IR2 and HIR m·min^{-1} found in this study is similar to that seen in soccer research[3]. In contrast to the present findings, previous studies in professional soccer have shown that more successful teams have more ball involvements but do not travel as far at high intensity[26], suggesting a different relationship between HIR m·min^{-1} and number of passes than that observed in this study. The different findings between these studies highlight the distinct differences in technical and tactical demands of teams between soccer and Australian Football.

This study also investigated the mediation relationship using conditional variables (moderators) such as position played and player experience. The indirect effect on the number of ball disposals strengthened for non-key position players when added as conditions for yo-yo IR2→HIR m·min^{-1}. It is likely that tactical constraints of playing key position (i.e. full forward, fullback, centre-half forward and centre-half back) may limit the space a player works in, thereby, limiting the player to work within their physical capabilities. Similar justification has been suggested for the differences in playing positions in soccer[27]. The present study also showed that the indirect effect was strengthened in non-key position players compared to key position players for HIR m·min^{-1}→number of ball disposals. This finding may be partly explained by the relatively limited exposure to the ball typically observed in key position players. Indeed, Dawson et al.[28] reported that key position players had less contest involvements compared to non-key position players. Therefore, limiting the space that a player can move in (i.e. imposed by either the players team strategy or opposition strategy) may reduce the importance of HIR m·min^{-1} for successful performance. Therefore, since key position players may not obtain the same performance benefits from having a high yo-yo IR2 score as non-key position players, they may benefit from focussing more training toward developing other physical capacities or technical abilities (i.e. muscular strength and power, repeated sprint ability, speed, defensive skills, goal kicking etc.).

Greater playing experience was also found to strengthen the relationship between HIR m·min^{-1} and number of ball disposals and moderate the indirect effect. This suggests that not only is the ability to perform HIR m·min^{-1} important to gaining ball disposals but experience may dictate whether a player has involvement with the ball. Whilst speculative, it is possible that more experienced players can read the play more effectively and place themselves in a more appropriate position to receive the ball and/or are more likely to beat an opponent in a one-on-one contest. Nonetheless, more research is still required to identify the specific characteristics experienced players possess that allows them to generate a greater number of ball disposals via the same HIR m·min^{-1} than their less experienced counterparts.

Conclusion

In summary, this is the first study to statistically model the effect yo-yo IR2 performance has on Australian Football performance. This is also the first study, to the author’s knowledge, to use mediation analysis in sports performance research. The results demonstrated that yo-yo IR2 performance affects the number of ball disposals gathered via HIR m·min^{-1}, and is strengthened in non-key position players and those who have played greater than 50 matches. It should be noted, however, that this study was conducted at the beginning of the season and further research should aim at identifying if this model is adaptable to the middle and latter stages of a season. Further research expanding on this model should seek to identify other moderators or cofounding variables that influence these effects, explain the effects of interchange on HIR m·min^{-1}, to identify if intervention to improve yo-yo IR2 or HIR m·min^{-1} will alter the number of ball disposals, and to identify the impact of number of ball disposals on the outcome of the match.

Practical Implications

- Non-key position players may improve their ball disposal count by improving their yo-yo IR2 score.
- Improvements in yo-yo IR2 score may improve match HIR m·min^{-1} in non-key position players at the beginning of the season.
- The mediation model provides a foundation to evaluate Australian Football performance.

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References

1. Coutts, A., Quinn, J., Hocking, J et al., Match running performance in elite Australian Rules Football. Journal of Science and Medicine in Sport, 2010. 13(5):543-8.
2. Rampinini, E., Coutts, A., Castagna, C. et al., Variation in top level soccer match performance. International Journal of Sports Medicine, 2007. 28:1018-24.
3. Castagna, C., Impellizzeri, F. M., Cecchini, E. et al., Effect of intermittent-endurance fitness on match performance in young male soccer players. Journal of Strength and Conditioning Research, 2009. 23(7):1954-9.
4. Iaia, F.M., E. Rampinini, and J. Bangsbo, High-intensity training in Football. International Journal of Sports Physiology and Performance, 2009. 4:291-306.
5. Impellizzeri, F.M. and S.M. Marcora, Test validation in sport physiology: Lessons learned from clinimetrics. International Journal of Sports Physiology and Performance, 2009. 4:269-77.
6. MacKinnon, D.P., A.J. Fairchild, and M.S. Fritz, Mediation analysis. Annual Review of Psycology, 2007. 58:593-614.
7. Mohr, M., P. Krustrup, and J. Bangsbo, Match performance of high-standard soccer players with special reference to development of fatigue. Journal of Sports Sciences, 2003. 21:519-28.
8. Helgerud, J., Engen, L. C., Wisloff, U et al., Aerobic endurance training improves soccer performance. Medicine & Science in Sports & Exercise, 2001. 33(11):1925-31.

9. Impellizzeri, F.M., Marcora, S. M., Castagna, C et al., Physiological and performance effects of generic versus specific aerobic training in soccer players. International Journal of Sports Medicine, 2006. 27(6):483-92.

10. Young, W., Newton, R. U., Doyle, T. L et al., Physiological and anthropometric characteristics of starters versus non-starters and playing position in elite Australian Football: A case study. Journal of Science and Medicine in Sport, 2005. 8(3):333-45.

11. Pyne, D.B., Gardner, A. S., Sheehan, K et al., Fitness testing and career progression in AFL football. Journal of Science and Medicine in Sport, 2005. 8(3):321-32.

12. Banister EW. Physiological Testing of the High Performance Athlete. In: MacDougall JD, Wender HA, Gree HJ, editors. Champaign, IL: Human Kinetics; 1991. 403-24.

13. Bradley, P.S., Mohr, M., Bendiksen, M et al., Sub-maximal and maximal Yo-Yo intermittent endurance test level 2: heart rate response, reproducibility and application to elite soccer. European Journal of Applied Physiology, 2010;111(6):969-78.

14. Cormack, S.J., Newton, R. U., McGuigan, M. R et al., Neuromuscular and endocrine responses of elite players during an Australian rules football season. Int J Sports Physiol Perform, 2008. 3(4):439-53.

15. Bangsbo, J., F.M. Iaia, and P. Krustrup, The yo-yo intermittent recovery test: A useful tool for evaluation of physical performance in intermittent sports. Sports Medicine, 2008. 38(1):37-51.

16. Young, W. and L. Prior, Relationship between pre-season anthropometric and fitness measures and indicators of playing performance in elite junior

Australian Rules football. Journal of Science and Medicine in Sport, 2007. 10:110-18.

17. Jennings, D., Cormack, S., Coutts, A. J et al., The validity and reliability of GPS units in team sport specific running patterns. International Journal of Sports Physiology and Performance, 2010. 5(3):328-41.
18. Heasman, J., Dawson, B., Berry, J et al., Development and validation of a player impact ranking system in Australian football. International Journal of Performance Analysis in Sport, 2008. 8(3):156-71.
19. O'Shaughnessy, D.M., Possessions versus position: Strategic evaluation in AFL. Journal of Sports Science and Medicine, 2006. 5:533-40.
20. Cormack, S., Newton, R. U., McGuigan, M. R et al., Neuromuscular and endocrine responses of elite players during an Australian Rules football season. International Journal of Sports Physiology and Performance, 2008. 3:439-53.
21. Bland, J.M. and D.G. Altman, Cronbach's alpha. British Medical Journal, 1997. 314(7080): 572.
22. Preacher, K.J. and A.F. Hayes, Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. Behaviour Research Methods, 2008. 40(3): 879-91.
23. Batterham, A.H., WG, Making meaningful inferences about magnitudes. International Journal of Sports Physiology and Performance, 2006. 1: 50-7.
24. Preacher, K.J., D.D. Rucker, and A.F. Hayes, Addressing Moderated Mediation Hypotheses: Theory, Methods, and Prescriptions. Multivariate Behavioral Research, 2007. 42(1): 185-227

25. Wells, G.D., M. Elmi, and S. Thomas, Physiological correlates of golf. Journal of Strength and Conditioning Research, 2009. 23(3):741-50.

26. Rampinini, E., Impellizzeri, F. M.,Castagna, C et al., Technical performance during soccer matches of the Italian Sere A league: Effect of fatigue and competitive level. Journal of Science and Medicine in Sport, 2009. 12(1): 227-33.

27. Di Salvo, V., Baron, R., Tschan, H et al., Performance characteristics according to playing position in elite soccer. International Journal of Sports Medicine, 2007. 28: 222-7.

28. Dawson, B., Hopkinson, R., Appleby, B et al., Player movement patterns and game activities in the Australian Football league. Journal of Science and Medicine in Sport, 2004. 7(3):278-91.

Chapter 4: Impact of Neuromuscular Fatigue on Match Exercise Intensity and Performance in Elite Australian Football

Abstract

Objective: This study aimed to quantify the influence of neuromuscular fatigue (NMF) via flight time to contraction time ratio (FT:CT) obtained from a countermovement jump on the relationships between yo-yo intermittent recovery (level 2) test (yo-yo IR2), match exercise intensity (HIR m·min^{-1} and Load™·min^{-1}) and Australian football performance.

Method: Thirty seven data sets were collected from 17 different players across 22 elite Australian Football matches. Each data set comprised an athlete's yo-yo IR2 score prior to the start of the season, match exercise intensity via Global Positioning System and on-field performance rated by coaches' votes and number of ball disposals. Each data set was categorised as normal (>92% baseline FT:CT, n = 20) or fatigued (<92% baseline FT:CT, n = 17) from a single countermovement jump performed 96 hours after the previous match. Moderation-mediation analysis was completed with yo-yo IR2 (independent variable), match exercise intensity (mediator) and Australian Football performance (dependent variable) with NMF status as the conditional variable. Isolated interactions between variables were analysed by Pearson's correlation and effect size statistics.

Results: Yo-yo IR2 score showed an indirect influence on number of ball disposals via HIR m·min^{-1} regardless of NMF status (normal FT:CT indirect effect = 0.019 p <0.1, reduced FT:CT indirect effect = 0.022 p <0.1). However, yo-yo IR2 score only influenced coaches' votes via Load™·min^{-1} in the non-fatigued state (normal: FT:CT indirect effect = 0.007 p <0.1, reduced: FT:CT indirect effect = -0.001 p > 0.1). In isolation, NMF status also reduces relationships between yo-yo IR2 and load™·min^{-1}, yo-yo IR2 and coaches votes, Load™·min^{-1} and coaches' votes (Δr > 0.1).

Conclusion: Routinely testing yo-yo IR2 capacity, NMF via FT:CT and monitoring Load™·min^{-1} in conjunction with HIR m·min^{-1} as exercise intensity measures in elite Australian football is recommended.

Key words: Load, Global Positioning System, Physical Capacity

Introduction

Fatigue is often described as the inability to maintain force or power output at the required level[1]. Whilst a number of models have been proposed to describe the mechanisms underlying reductions in work output, many of these may be considered to have acute and often transient performance limitations[1]. A major area of interest for researchers and practitioners alike is the influence of various longer term fatigue states on athletic performance (fatigue-recovery cycle timeline) and more specifically, discovering effective methods of assessing fatigue[2]. Specifically, the assessment of neuromuscular fatigue (NMF) via flight time : contraction time ratio (FT:CT) has been shown to be a useful tool to monitor fatigue status in elite Australian Football players[2].

Recent studies have investigated the immediate physical consequence of team sport or simulated team sport running, demonstrating reductions in muscle strength and muscle activation[3, 4]. Furthermore, FT:CT from a single countermovement jump (CMJ) has also been shown to be supressed for up to 72 hours post an elite Australian Football match[2]. An inability to recover neuromuscular function in accordance with the normal fatigue-recovery cycle may have implications on performance[5]. Currently it is unclear if a suppression of neuromuscular function (in the form of lower FT:CT) will impact on the physical activity profile of elite Australian Football players.

Recently, the importance of high intensity running (distance covered at > 15 km/h) to elite Australian Football performance has been demonstrated to positively influence performance at the beginning of the season and similar findings have been reported in elite soccer[6-8]. It has been established that this type of running is a discriminator of high and low performing teams within a competition level and between leagues of different standards[9]. Importantly, high intensity running in Australian Football is subject to an athlete's physical capacity specifically measured by yo-yo Intermittent Recovery Test (level 2) score (yo-yo IR2)[8]. A specific sequence (or domino effect) was established with yo-yo IR2 capacity affecting the amount of HIR $m \cdot min^{-1}$ accumulated, which in turn influences the number of ball disposals gained in elite Australian Football[8]. This suggests that without affecting HIR $m \cdot min^{-1}$, yo-yo IR2 score does not (independently) affect performance. It has also been demonstrated that yo-yo performance does not significantly change across a competitive season in elite soccer[10]. Both soccer and Australian Football have reported similar exercise intensities, yet Australian Football involves approximately 10 minutes greater volume (90 vs. 100 minutes)[7, 11]. As is the case in soccer[3], the match is the greatest training stimuli during the competition phase. Therefore, substantial alterations in high intensity running throughout the season are likely due to the influence of fatigue rather than a change in yo-yo IR2.

Match exercise intensity is generally measured via derivatives of distance, gathered from micro-technology such as Global Positioning Systems (GPS), but recently has also been measured by accelerometers[12]. An accelerometer measures the tri-axial change of inertia (acceleration) at 100Hz making it much more sensitive to subtle movements than GPS that measures global displacement at only 1 – 10 Hz. The summation of the tri-axial accelerations is determined as "Load™" and a detailed description and calculation of Load™ has been presented by Boyd et al.[12]. Unlike GPS, it is unclear if the accumulation of accelerometer Load™ is influenced by physical capacity (yo-yo IR2), provides any indication of physical performance of Australian Football players, or is sensitive to NMF in the elite Australian Football population.

The aforementioned factors (physical capacity, match exercise intensity and neuromuscular fatigue) have all been found to influence elite Australian Football performance[5, 8]. However, the manner in which these variables interact to influence elite Australian Football performance across an entire season remains vague. Therefore, this study aimed to identify: 1) if NMF influences Australian Football performance by affecting associations between yo-yo IR2 and performance (coaches' votes and number of ball disposals) across an entire season, 2) if NMF influences the relationship between yo-yo IR2 and match exercise intensity (HIR $m \cdot min^{-1}$ and Load™$\cdot min^{-1}$) and 3) if NMF affects the relationship between Load™$\cdot min^{-1}$ and other reliable exercise intensity measures ($m \cdot min^{-1}$ & HIR $m \cdot min^{-1}$) . It is hypothesised that NMF will alter the relationships between physical capacity, match exercise intensity and match performance in elite Australian Football players.

Methods

This study was a prospective longitudinal design. Common Australian Football performance measures were used as dependant variables, whilst the yo-yo IR2 test as a measure of physical capacity was used as the independent variable. Match exercise intensity measures were included as mediators (link between dependant and independent variables) and NMF was included as a conditional variable (moderator) (see Figure 4.1 and Appendix A).

Seventeen elite Australian Football players with a mean (±SD) stature of 187.6 ±7.3 cm, mass of 86.5 ±8.7 kg and age of 22.3 ±3.3 years provided data for this research. Informed consent was gathered prior to the commencement of the studies. Ethical approval was obtained by the University Research Ethics Committee. Participants were informed of the risks of the study in person and writing, signed an informed consent document prior to the beginning of data collection and were free to withdraw from the study at any time.

The participants were professional elite players participating in the Australian Football League. Participants were completing between seven and nine training sessions per week including various sessions (such as recovery, skills, weights, flexibility and matches) and a day off mid-week.

All participants completed the yo-yo IR2 test (independent variable) before the start of the season, were selected to play for the first grade team, provided match exercise intensity (mediator) at least once during the season (gathered via GPS device during match), performed a single counter movement jump to obtain FT:CT ratio prior to the upcoming match (moderator/conditional variable) and had match performance records (dependent variables: number of ball disposals and coaches' votes) collected post match from any of the 22 matches of the competitive season. Each match was treated as an independent sample. A total of 37 samples were obtained with subjects providing between 1 and 4 samples each.

The players performed the single countermovement jump on a force plate (400 series force plate; Fitness Technology, Adelaide, Australia) operated by manufacturer software (Ballistic Measurement System, Fitness Technology). The ratio of FT:CT was calculated using custom software (TLAD Athlete Solutions, Melbourne, Australia). The assessment of FT:CT was conducted according to previously established protocols, which has been demonstrated as both valid and reliable (CV = 8%) in elite Australian Football players[5, 13]. All subjects were familiarised with the procedures during four practice trials. Baseline testing was calculated as the four week mean leading into the first match (conducted during the taper of the pre-competition phase) of the 22 match season which allowed a fatigue free competition phase baseline. Weekly tests were conducted a minimum of 96 h post match (the day after the day off), which according to previous work would be long enough to allow a return to baseline values if athletes followed the expected fatigue-recovery cycle[2]. Players performed a standardised warm up including 2 minutes of aerobic exercise, dynamic flexibility movements and 3 practise jumps prior to collection of weekly data in accordance with established protocols[2]. Testing procedures were conducted at the same time of day 0900 – 1000 h. Weekly values were calculated as a percentage of the baseline and then categorised as *fatigued* or *normal* based on the natural biological fluctuation of 8% in this population[6].

All participants had their match exercise intensity recorded by a portable GPS unit sampling at 5 Hz whilst the internal accelerometer (housed inside the same GPS device) sampled at 100 Hz (MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia). Match exercise intensity and performance measures were gathered from all 22 matches of a single season. Global positioning system data was downloaded post match using manufacturer specific software (Logan Plus v. 4.4.0) for analysis.

The participants were analysed for hypohydration status one day prior to all matches and on the morning of match day to ensure dehydration would not affect the match exercise intensity or performance. Players also followed a nutrition plan directed by a sports dietician throughout the season to ensure they were appropriately fuelled for optimal performance. Match exercise intensity was only recorded for the on-field playing duration of each participant. To reduce the likelihood of reporting artificially high match exercise intensities, match activity profiles were only accepted for analysis if the participant played ≥70% of total match time and absolute variables were divided by the on field duration[14]. Variables collected from the GPS units were distance travelled per minute ($m \cdot min^{-1}$), distance travelled at high intensity per minute (HIR $m \cdot min^{-1}$) where HIR m =distance travelled above 15 $km \cdot h^{-1}$ and accelerometer Load™ per minute (Load™$\cdot min^{-1}$), as described previously[8]. These variables have been tested for reliability and validity; high intensity distance (striding and sprinting) CV = 9.0–11.9% (activity dependent), validity range -6.2–4.6% (activity dependent)[15] whilst Load™·min^{-1} has shown a CV of < 2% [12].

The participants' number of ball disposals were collected by a commercial statistical analysis company (Champion Data©, South Bank, Australia). Champion data have been reported to have a 99% accuracy rate for match statistics[16]. Coaches' votes were also collected post match from five assistant coaches. Coaches rated every players performance within 60 mins post match on a 1 – 5 scale (1 = poor performance – 5 = excellent performance). An aggregate score was given to each player per match similar to previous protocols[5, 17]. The aggregate score has been shown to have acceptable internal consistency (Cronbach's α ranging 0.88 – 0.92)[8].

To investigate the interaction of the variables, moderated-mediation model 5 was employed, where the moderator (FT:CT) interacts with both the *a* and *b* mediation paths with bootstrap resampling method as described in previous work (see Figure 4.1)[18]. A comprehensive description of mediation and moderation analysis has been provided by others[18].

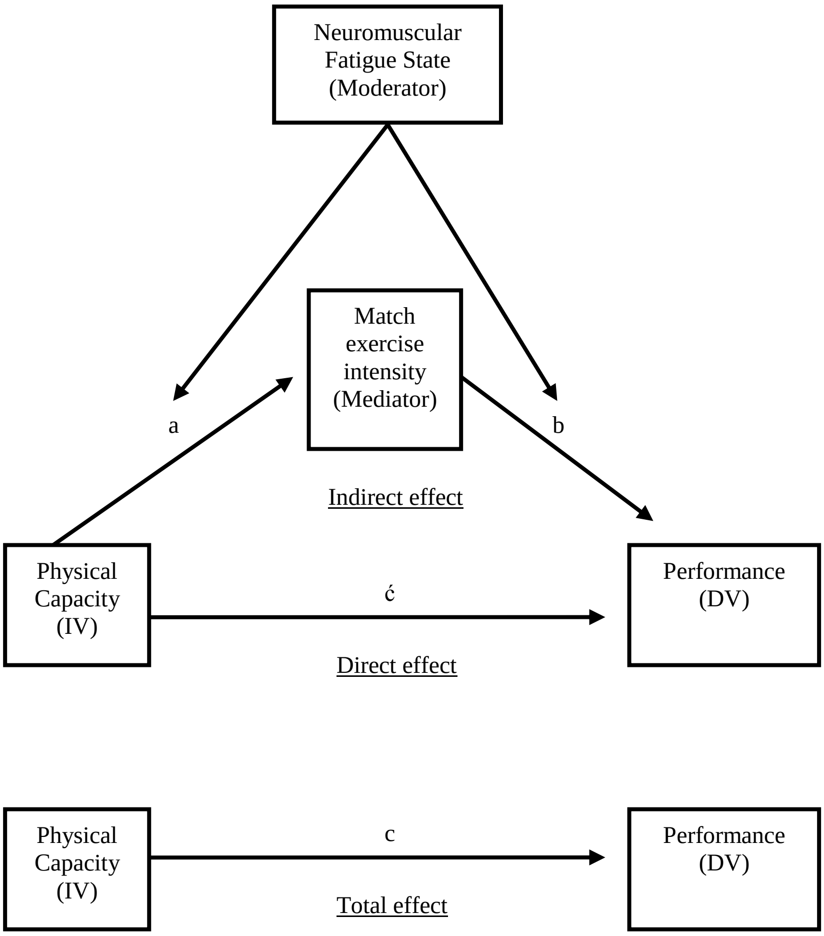

Figure 4.1: The interaction being tested in mediation-moderation analysis. IV represents the independent variable, DV represents the dependant variable. The indirect effect is the effect the IV has on the DV through the mediator (a X b). The direct effect (ć) is the effect the IV has on the DV controlling for the mediator. The total effect (c) is the effect of the IV on the DV not controlling any other variable. The moderator is the conditional variable separating the analysis into 2 mediation analyses (normal and fatigued states).

Individual FT:CT were categorised as either *normal* or *fatigued* from baseline based on a change greater than the biological fluctuation of 8% reported in previous literature[13]. Moderation-Mediation effect was analysed in SPSS v.17 (SPSS Inc., Chicago, USA) using macro and syntax from Preacher, Rucker and Hayes (moderation-mediation), using a significance criteria of <0.1[18]. This significance level was chosen as the standard <0.05 significance criteria may be too conservative for detecting important practical changes in the elite sport environment[8, 19].

Once a difference in the indirect effect was identified (based on significance of indirect effect), the individual relationships were separated for *normal* and *fatigue* FT:CT and analysed using a magnitudes based approach. This was done by calculating a Pearson's correlation coefficient and the 75% likelihood of a change in correlation exceeding 0.1 using a custom Excel spreadsheet[21, 22]. A qualitative criteria was given to the per cent likelihood of a practically meaningful correlation (> 0.1) and was categorised as most unlikely (0.5 – 4.9%), very unlikely (5 – 24.9%), unlikely (25 – 74.9%), possible (75 – 94.9%), likely (95 – 99.5%) and most likely (100%)[22]. In addition, variables were log transformed to reduce bias due to non-uniformity of error and each path was analysed for the magnitude of the difference in mean of the dependant variable (DV), after controlling for the independent variable (IV) in both *normal* and *fatigued* states[22]. A practically important difference was determined as a > 75% chance of the ES exceeding 0.2[23]. The magnitude of the change in the ES (when controlled for change in dependent variable) was classified as negligible (0.0 – 0.19); small (0.2 – 0.59); moderate (0.6 – 1.1); large (1.2 – 1.9); very large (> 2.0)[23].

Results

The mean ±SD of the yo-yo IR2, HIR $m \cdot min^{-1}$, Load™$\cdot min^{-1}$, number of ball disposals and coaches' votes were 1028 ± 190 m, 38.8 ± 11.6 $m \cdot min^{-1}$, 15.7 ± 3.1 arbitrary units$\cdot min^{-1}$, 16.5 ± 6.0 disposals and 11.5 ± 4.1 votes respectively. Yo-yo IR2 showed a significant indirect effect on ball disposals through HIR $m \cdot min^{-1}$ in both *normal* (n = 20) and *fatigued* (n = 17) FT:CT state (Table 4.1). Yo-yo IR2 showed a significant indirect effect on coaches' votes through Load™·min in only the *normal* FT:CT group.

Table 4.1: The indirect effect of the independent variable (X) and mediator (M) on the dependant variable (Y) when separated for flight time contraction time ratio (FT:CT).

		Normal FT:CT		Reduced FT:CT	
X→M→Y	**Boot sample (n)**	**Boot indirect effect**	**Boot p-value**	**Boot indirect effect**	**Boot p-value**
Yo-yo IR2→HIR m·min^{-1}→ball disposals	3000	0.019 (0.006)	0.00*	0.022 (0.011)	0.03*
Yo-yo IR2→ HIR m·min^{-1}→coaches' votes	3000	0.003 (0.008)	0.71	-0.122 (0.012)	0.31
Yo-yo IR2→ Load™·min^{-1} →ball disposals	3000	0.005 (0.006)	0.34	-0.001 (0.004)	0.77
Yo-yo IR2→Load™·min^{-1} →coaches' votes	3000	0.007 (0.004)	0.09*	-0.001 (0.004)	0.77

Normal = > 92% of baseline and Reduced = < 92% of baseline. Indirect effects are represented by regression coefficients with standard errors in parentheses. *Boot* indicates the results are derived from bootstrap resampling technique. * indicates significance at the 0.1 level.

Table 4.2 illustrates the strength of the change in isolated relationships. All interactions showed meaningful positive correlations in the *normal* FT:CT state. However, only the relationship between yo-yo IR2 and Load™·min maintained a meaningful positive correlation in a *fatigued* FT:CT state. Furthermore, the changes in correlations are all > 75% likely to be greater than the criteria r = 0.1 representing a practically important change in relationship from the *normal* to *fatigued* FT:CT state. When the paths were isolated, the *a* path (yo-yo IR2 and Load™·min^{-1}, see Figure 4.1) showed no mean difference in Load™·min between *normal* and *fatigued* FT:CT (adjusted for yo-yo IR2). However, there was a mean reduction in coaches' votes in the fatigued FT:CT state (adjusting for either yo-yo IR2 or Load™·min^{-1}).

Table 4.2: Changes is mean and correlation when separated into normal and fatigued groups.

	Normal FT:CT			Fatigued FT:CT			Difference	
IV→DV	**n**	**Adjusted mean of DV**	**r**	**n**	**Adjusted mean of DV**	**r**	**Difference in adjusted mean after log transformation (ES)**	**Δr**
Yo-yo IR2 → Load™·min^{-1}	20	15.4 (1.81)	0.77±0.17 very likely	17	16.3 (3.7)	0.33±0.38 likely	0.33±0.57 unclear	0.44±0.26 very likely
Load™·min^{-1}→coaches' votes	20	12.83 (3.34)	0.51±0.27 very likely	17	10.5 (4.5)	-0.22±0.4 possible	-0.67±0.56 large-trivial	0.73±0.43 very likely
Yo-yo IR2→coaches' votes	20	12.41 (3.53)	0.38±0.33 likely	17	10.28 (4.5)	-0.17±0.4 possible	-0.60±0.56 moderate-trivial	0.54±0.48 likely
Yo-yo IR2→coaches' votes (controlling Load™·min^{-1})	20		-0.03±0.38 unclear	17		-0.1±0.41		0.07±0.54 unclear

Means of the dependant variable (DV) are represented by adjusted mean for differences in independent variable (IV) ± standard error of the estimate. Pearson correlation coefficients (r) are presented with ± 90% confidence intervals. Differences in means are represented by Cohen's effect size (ES) ± 90% confidence interval with qualitative descriptor whilst magnitude of difference in correlations (Δr) are represented by r ± 90% confidence interval and qualitative descriptor.

Table 4.3 shows that the relationship between Load™·min^{-1} and m·min^{-1} does not change in the presence of NMF, nor does the mean of m·min^{-1} change (adjusting for Load™·min^{-1}). Furthermore, the relationship between Load™·min^{-1} and HIR m·min^{-1} was meaningfully reduced in the fatigued state. In addition, there was a practically important difference in HIR m·min^{-1} between the *normal* and *fatigued* groups (adjusting for changes in Load™·min^{-1}).

Table 4.3: The difference in mean and in relationship between Load™ per minute (Load™·min^{-1}) and distance per minute (m·min^{-1}) and Load™·min^{-1} and distance at high intensity per minute (HIR·min^{-1}) when separated into Normal and Fatigued groups.

	Normal FT:CT			**Fatigued FT:CT**			**Difference**	
IV → DV	**n**	**Adjusted mean of DV**	**r**	**n**	**Adjusted mean of DV**	**r**	**Difference in adjusted mean after log transformation (ES)**	**Δr**
Load™·min^{-1} → m·min^{-1}	20	137.8 (7.8)	0.76±0.17 most likely	17	133.7 (12.5)	0.58±0.29 very likely	-0.37±0.56 unclear	0.18±0.27 unclear
Load™·min^{-1} → HIR m·min^{-1}	20	41.5 (7.2)	0.74±0.19 most likely	17	36.9 (9.9)	0.31±0.38 likely	-0.47±0.56 moderate-trivial	0.43±0.29 very likely

Means of the dependant variable (DV) are represented by adjusted mean for differences in independent variable (IV) ± standard error of the estimate. Pearson correlation coefficients (r) are presented with ± 90% confidence intervals. Differences in means are represented by Cohen's effect size (ES) ± 90% confidence interval with qualitative descriptor whilst magnitude of differences in correlations (Δr) are represented by r ± 90% confidence interval and qualitative descriptor.

Discussion

This study hypothesised that NMF would affect relationships between physical capacity, match exercise intensity and elite Australian Football performance. The results highlight four novel findings that support this hypothesis. First FT:CT influences (moderates) the effect of yo-yo IR2 and Load™·min^{-1} on coaches' votes (ES -0.6 ± 0.56 and -0.67 ± 0.56 reduction in the fatigued state respectively). Secondly, we have validated Load™·min^{-1} as a useful match exercise intensity measure in Australian Football. Finally, the presence of NMF appears to alter the way in which Load™·min^{-1} is produced. However, NMF did not influence the relationships between yo-yo IR2, HIR m·min^{-1} and number of ball disposals[8].

This study identified a reduction in FT:CT exceeding the 8% CV has a direct negative effect on the relationship between Load™·min^{-1} and coaches' votes. The mechanics to produce the same output (i.e. Load™·min^{-1}) appear to be altered with reductions in FT:CT[13], and this change is perceived negatively by coaches. This is a similar finding to previous research that found a small correlation between raw change in FT:CT from baseline and coaches' votes one week prior to a match in Australian Football players of the same level of competition as the current study[5]. A potential hypothesis is that Australian footballers may become inefficient in the production of a given Load™·min^{-1}. For example, they may be slower to accelerate, thus arrive late to contests or have a reduced ability to evade an opponent. This may result in players achieving the same Load™·min^{-1} but in a different and undesirable manner (i.e. greater subtle lateral or vertical movements in a NMF fatigued state to produce a given Load™·min^{-1}).

A meaningful change in relationship between Load™·min^{-1} and HIR m·min^{-1} ($\Delta r = 0.43 \pm 0.29$), and not Load™·min^{-1} and m·min^{-1} ($\Delta r = 0.18 \pm 0.27$) in the fatigued state also suggests an alteration in activity profile in a fatigued state. Previously, very high correlations have been observed between Load™ and distance ($r^2 = 0.90$)[24]. Although, this study shows that this particular relationship remains stable in the presence of NMF, it is clear that the relationship between Load™·min^{-1} and HIR m·min^{-1}is altered. A potential explanation for this is that players alter the way they accumulate Load™ and this alteration is perceived poorly by coaches. A movement efficiency concept in Australian Football has been suggested previously, with more experienced players obtaining a higher number of disposals for a given HIR m·min^{-1} than less experienced players[8].

Another important finding from this study was the change in correlation between yo-yo IR2 and Load™·min^{-1} from normal to fatigued states ($\Delta r = -0.44 \pm 0.26$). The difference in correlation between the two conditions suggests that in the fatigued state, the importance of yo-yo IR2 to the production of Load™·min^{-1} is reduced. Critically, this occurs without a practically important change (ES 0.33 ± 0.57) in mean Load™·min^{-1} when adjusted for yo-yo IR2 performance, regardless of fatigue status. This appears to confirm the notion that elite Australian Football players are able to produce a similar output (as measured by Load™·min^{1}) when fatigued, however the movements contributing to the accumulation of Load™·min^{-1} are less dependent on capacity (i.e. produced at a lower intensity).

As HIR m·min^{-1} (when corrected for yo-yo IR2) was not altered by NMF, it is also plausible performance (as assessed by coaches) is influenced more heavily by effectiveness than total work output. Players experiencing NMF may continue to have high output (i.e. HIR m·min^{-1} and Load™·min^{-1}) but undergo changes to mechanical efficiency that result in movement patterns viewed as ineffective by coaches. Players with NMF may be able to maintain overall high intensity running performance but actually perform more work at lower levels of this intensity band (i.e. < 24 km·h^{-1}). Neuromuscular fatigue present prior to elite handball matches has also been coupled with reductions in sprint performance, and this supports the concept that NMF may reduce the ability to perform maximum intensity efforts[25].

Interestingly, a mediation relationship was observed between yo-yo IR2 and number of disposals through HIR m·min^{-1} across an entire season, which is a similar finding to previous research that investigated this mediation during the first half of a season[8]. We hypothesised that NMF may have disrupted this relationship, however yo-yo IR2 remains associated with number of disposals via HIR m·min^{-1}. Therefore, variability in HIR m·min^{-1} throughout a season may be a result of factors other than NMF, such as playing conditions, strategic or psychological factors, or other forms of acute or cumulative fatigue. Regardless of NMF status, the current data suggests that the yo-yo IR2 test provides a strong indication of the overall HIR m·min^{-1} that can be performed by players during the entire season.

Although this study has high ecological validity, some limitations were apparent with the study design and should be noted. For example, the psychological state of the players prior to the match was not tested prior to each performance. Whilst real world elite sporting performance imposes some limitations on the ability to completely control the environment, the results of the current research are clear and unlikely to have been influenced by extraneous factors. As a result, there are clear practical implications for performance.

Conclusion

This study is the first to demonstrate the effect of NMF on Australian Football performance by negatively influencing the relationships between yo-yo IR2 and coaches votes through

Load™·min^{-1}. Furthermore, it was identified yo-yo IR2 can reflect the number of ball disposals through-out the entire season via HIR m·min^{-1}, regardless of NMF. Additionally, the results of this study validates Load™·min^{-1} as a useful exercise intensity measure in elite Australian Football. It also suggests that NMF status can affect the association of Load™·min^{-1} with other match exercise intensity measures.

Practical Implications

- Load™·min^{-1} and HIR m·min^{-1} influence performance and should be used for the assessment of exercise intensity in elite Australian Football players.

- Neuromuscular fatigue via FT:CT influences performance and should be routinely conducted in elite Australian Football.

- Yo-yo IR2 tests provide an indication of the HIR m·min^{-1} a player can perform throughout the entire season and should be included in an Australian Football testing battery.

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References

1. Lorenzen C, Williams MD, Turk PS, Meehan DL, Kolsky DJ. Relationship between velocity reached at VO2(max) and time-trial performances in elite Australian Rules footballers. International Journal of Sports Physiolology and Performance. 2009;4(3):408-11.
2. Cormack SJ, Newton RU, McGuigan MR. Neuromuscular and endocrine responses of elite players to an Australian rules football match. International Journal of Sports Physiolology and Performance. 2008;3(3):359-74.
3. Rahnama N, Reilly T, Lees A, Graham-Smith P. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. Journal of Sports Science. 2003;21(11):933-42.
4. Oliver JL, Armstrong N, Williams C. Changes in jump performance and muscle activity following soccer-specific exercise. Journal of Sports Sciences. 2008;26(2):141-8.
5. Cormack SJ, Newton RU, McGuigan MR, Cormie P. Neuromuscular and endocrine responses of elite players during an Australian rules football season. International Journal of Sports Physiolology and Performance. 2008;3(4):439-53.
6. Helgerud J, Engen LC, Wisloff U, Hoff J. Aerobic endurance training improves soccer performance. Medicine & Science in Sports & Exercise. 2001;33(11):1925-31.
7. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. Journal of Sports Sciences. 2003;21:519-28.

8. Mooney M, O'Brien B, Cormack S, Coutts A, Berry J, Young W. The relationship between physical capacity and match performance in elite Australian football: A mediation approach. Journal of Science and Medicine in Sport. 2011;14(5):447-52.

9. Rampinini E, Impellizzeri FM, Castagna C, Coutts A, Wisloff U. Technical performance during soccer matches of the Italian Sere A league: Effect of fatigue and competitive level. Journal of Science and Medicine in Sport. 2009;12(1):227-33.

10. Bradley, P.S., Mohr, M., Bendiksen, M et al., Sub-maximal and maximal Yo-Yo intermittent endurance test level 2: heart rate response, reproducibility and application to elite soccer. European Journal of Applied Physiology, 2010;111(6):969-78.

11. Wisbey B, Montgomery P, Pyne DB, Rattray B. Quantifying movement demands of AFL football using GPS tracking. Journal of Science and Medicine in Sport. 2010;13(5):531-6

12. Boyd L, Ball K, Aughey RJ. The reliability of minimaxX accelerometers for measuring physical activity in Australian football. International Journal of Sports Physiology and Performance. 2011;6(3):311-21.

13. Cormack SJ, Newton RU, McGuigan MR, Doyle TL. Reliability of measures obtained during single and repeated countermovement jumps. International Journal of Sports Physiology and Performance. 2008;3(2):131-44.

14. Aughey RJ. Australian football player work rate: evidence of fatigue and pacing? International Journal of Sports Physiology and Performance. 2010;5(3):394-405.

15. Jennings D, Cormack S, Coutts AJ, Boyd L, Aughey RJ. The validity and reliability of GPS units for measuring distance in team sport specific running patterns. International Journal of Sports Physiology and Performance. 2010;5(3):328-41.

16. O'Shaughnessy D M. Possession versus position: strategic evaluation in AFL. Journal of Sports Science and Medicine. 2006;5(4):533-40.

17. Heasman J, Dawson B, Berry J, Stewart G. Development and validation of a player impact ranking system in Australian football. International Journal of Performance Analysis in Sport. 2008;8(3):156-71.

18. Preacher KJ, Rucker DD, Hayes AF. Addressing Moderated Mediation Hypotheses: Theory, Methods, and Prescriptions. Multivariate Behavioual Research. 2007;42(1):185-227.

19. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. International Journal of Sports Physiology and Performance. 2006;1(1):50-7.

20. Hopkins WG. Measures of reliability in sports medicine and science. Sports Medicine. 2000;30(1):1-15.

21. Hopkins WG. A spreadsheet for combining outcomes from two subject groups. Sports Science. 2006; 10: Available from: sportsci.org/2006/wghcom.htm.

22. Hopkins WG. A spreadhseet to compare means of two groups. Sportscience. 2007; 11: Available from: sportsci.org/2007/inbrief.htm#xcl2.

23. Aughey RJ. Applications of GPS technologies to field sports. International Journal of Sports Physiology and Performance. 2011;6(3):295-310.

24. Ronglan LT, Raastad T, Børgesen A. Neuromuscular fatigue and recovery in elite female handball players. Scandinavian Journal of Medicine & Science in Sports. 2006;16(4):267-73.

Chapter 5: The physiological contribution to performance in the yo-yo intermittent recovery (level 2) test in team sport athletes.

Abstract

Objective: To identify the physiological mechanisms contributing to yo-yo intermittent recovery (level 2) (yo-yo IR2) performance.

Method: Nineteen recreational Australian footballers underwent the yo-yo IR2 test and a maximal accumulated oxygen deficit (MAOD) test on a treadmill at a 1% gradient in a randomised counter-balanced order. The yo-yo IR2 test required the participants to perform 2 X 20 m shuttles at incrementally increasing speed in time to an audio beep with 10 s of recovery between shuttles. Maximal accumulated oxygen deficit procedures included 5 X 5 sub-maximal continuous runs whilst VO_2 was recorded for the final 2 min of each stage. Immediately following the sub-maximal runs the speed was incrementally increased to elicit maximal oxygen uptake ($\dot{V}O_{2max}$). After 35 min of passive rest participants ran at a speed equivalent to 115% of $\dot{V}O_{2max}$ until exhaustion where expired air was collected and MAOD was calculated. The relationships between variables were assessed using a Pearson's correlation, and partial correlations.

Results: Predicted maximum aerobic speed (MAS), relative aerobic intensity and $\dot{V}O_{2max}$ were significantly correlated with yo-yo IR2 performance. Furthermore high yo-yo IR2 performers also had higher predicted MAS, relative aerobic intensity and $\dot{V}O_{2max}$. However, when other associated variables were controlled none of the variables in isolation were correlated with yo-yo IR2 performance.

Conclusions: Yo-yo IR2 performance is comprised of a series of complex interactions between several variables and appears specific to the individual.

Therefore training may focus on individual weaknesses that may improve yo-yo IR2 performance.

Key Words: Maximal Aerobic Speed, Aerobic Power, Anaerobic Capacity, Maximal Accumulated Oxygen Deficit, Time to Exhaustion.

Introduction

Most team sports require athletes to perform numerous high intensity efforts with small amounts of recovery[1, 2]. Like other team sports, Australian Football coaches and physical trainers perform several field tests to identify the capabilities of the athlete to cope with the repeated high intensity demands of a match[3-6]. The field test shown to provide the best indication of on-field high intensity running performance in Australian Football is the yo-yo intermittent recovery (level 2) test (yo-yo IR2)[7,8].

The yo-yo IR2 test has previously been shown to elicit near maximum heart rate, highly elevate blood lactate concentration and reduce muscle creatine phosphate and glycogen concentration suggesting a maximal aerobic energy yield and a substantial anaerobic energy contribution[9]. Furthermore, the level of performance on this test has shown very large correlations with post-test blood lactate, H^+ accumulation, rate of lactate accumulation, large correlation with bicarbonate levels and time constant for VO_2 kinetics[10] whilst is moderately associated with maximal oxygen uptake ($\dot{V}O_{2max}$), 5 m sprint, 30 m sprint performance and agility[10-12]. One of the strengths of the yo-yo IR2 test in predicting performance is that it challenges a variety of physiological systems that interact in a similar way to match play in many team sports[13].

Given the demonstrated links between yo-yo IR2 performance and the team sport exercise intensity, team sport training programs may attempt to measure the success of training interventions using this test[7]. However, to train specifically for team sports in a progressive and periodised manner coaches and fitness trainers should consider the underlying physical requirements that contribute to yo-yo IR2 performance.

Currently, the relative contribution of aerobic qualities such as $\dot{V}O_{2max}$, relative submaximal intensity, running economy and maximal aerobic speed (MAS), and anaerobic qualities such as maximum accumulated oxygen deficit (MAOD) to the yo-yo IR2 are unknown. Therefore, this study aims to identify the underlying physical qualities important to yo-yo IR2 performance.

Methods

Nineteen male regional team sport athletes (Australian footballers) from various teams volunteered to participate in this study. The participants were competing in various regional competitions of a similar standard and completed at least 5 hours of Australian Football specific activity per week (training and matches), and had a mean (±SD) stature of 180 ± 5 cm, mass of 78.0 ± 6.0 kg and age of 20.7 ± 1.6 years. Written informed consent was collected from each participant prior to the beginning of the study. Ethical approval was obtained from the University Research Ethics Committee (see Appendix B).

Each participant was required to complete both the yo-yo IR2 test and a MAOD test within 2 weeks. Participants completed the procedures in a randomised, counter-balanced order.

The yo-yo IR2 test was completed on a stable indoor surface using the procedures established previously[14]. Each participant underwent a practise session in order to familiarise themselves with the required running pace. These procedures have been found to be reliable and applicable to team sports such as soccer and Australian Football[7, 14]. Participants were required to perform 2 x 20 m shuttles in time to an audio beep of progressively increasing intensity with 10 s rest between shuttles in which the participant walked around a cone situated 5 m past the start/finish line. Each participant received a warning if they did not make the shuttle in time, upon missing a second time they were eliminated from the test. The total distance covered in metres during the test was deemed their yo-yo IR2 score.

The MAOD protocol was conducted in a laboratory on a motorised treadmill ergometer at 1% gradient (Cosmed, Italy) to replicate the energy cost of over ground running[15]. The participants were required to perform 5 X 5 min continuous sub-maximal runs at 8, 9.5, 11, 12.5 and 14 km·h^{-1}. Participants were fitted to a two-way breathing apparatus (Hans Rudolph, USA) through which expired air was analysed by an online metabolic system (Moxus, USA). The volume of oxygen consumption was recorded every 30 s and mean for the final two min of each 5 min period[16]. Continuing without rest from the final sub-maximal run, the intensity was increased by 1 km·h^{-1} every minute until ventilatory exhaustion and VO_2 plateau to obtain $\dot{V}O_{2max}$. Sub-maximal relative aerobic intensity was calculated to be the mean VO_2 (mL·kg^{-1}·min^{-1}) during the final two min of the 12.5 km·h^{-1} stage presented as a percentage of $\dot{V}O_{2max}$. Running economy was determined as the actual steady state VO_2 (mL·kg^{-1}min^{-1}) during the 12.5 km·h^{-1} stage.

The mean VO_2 for the final two min of each of the five sub-maximal run speeds was used to develop a linear regression model to determine the supra-maximal treadmill speed required at 115% of $\dot{V}O_{2max}$. The coefficient of determination was very high ranging from $r^2 = 0.93 – 0.99$ which is similar to others[17, 18]. The $\dot{V}O_{2max}$ of the participant was substituted into the regression equation to determine their predicted MAS. Participants were given 35 min of passive rest before completing the supra-maximal run to exhaustion.

Participants ran at a speed calculated to reflect 115% of $\dot{V}O_{2max}$ on a 1% gradient until exhaustion. Participants waited until the treadmill reached the prescribed speed then lowered themselves onto the treadmill belt. Data collection began when the participant removed their hands from the rails of the treadmill. Collection ceased once the participant indicated they could no longer maintain the speed by either a stop button on the side of the treadmill or a non-verbal signal to the test administers. The participants were fitted with a two-way breathing apparatus with expired air being collected directly by Douglas bags and analysed using first principles[19]. The expired air was pumped into a metabolic system to determine the O_2 and CO_2 concentrations at a rate of 3L per min, extraction was timed and the residual volume was included in the calculations. Expired air was then extracted manually by a 2L syringe until empty to determine the total volume of air. The volume of air was then standardised for pressure, water content, temperature and N^+ content. VO_2 was then calculated as below (Equation 1). The VO_{2I} was calculated using the Haldane transformation whist the VO_{2E} was calculated from the percentage of O_2 content multiplied by the standardised volume.

Eq 5.1. $VO_2 = VO_{2I} - VO_{2E}$

VO_2 = Oxygen uptake

VO_{2I} = Volume of Oxygen inspired

VO_{2E} = Volume of Oxygen expired

The MAOD was then calculated as the predicted VO_2 subtracted from the actual VO_2 as previously described[16, 20]. The duration of the supra-maximal run was also recorded.

Following the testing procedures, all data underwent and satisfied normality assumptions via a Kolmogorov-Smirnov test. A Pearson's correlation coefficient matrix was employed to identify interactions between all variables.

In addition, the data was separated into *high* and *low* yo-yo IR2 scores using median split technique. All variables were then analysed for differences between *high* and *low* yo-yo IR2 groups using a one-way ANOVA. Partial correlations were also used to isolate the contribution of variables independent of other associated variables (found in the correlation matrix)[21]. This was done in order to isolate the relationship between the independent and dependant variable controlling for other associated variables. Therefore, allowing a more precise evaluation of the actual contribution of the independent variable to the dependant variable without cofounding influences from other associated variables. All correlations were calculated in SPSS v.17 (SPSS Inc., Chicago, USA) with statistical significance set at the 0.05 level.

Results

The participant's mean ± SD for all variables are presented in Table 5.1. A correlation matrix between measured variables is also presented in Table 5.2.

Table 5.1: Descriptive analysis of the physiological variables tested**.**

Variables	n	Mean ± SD
$\dot{V}$**O$_{2max}$** (mL·kg·min^{-1})	19	56.5 ± 5.9
MAOD (mL O_2 eq·kg·min^{-1})	19	13.7 ± 6.0
Relative aerobic intensity (%$\dot{V}O_{2max}$ at 12.5 km·h^{-1})	19	84.1 ± 7.9
Running Economy (VO_2 mL·kg·min^{-1}at 12.5 km·h^{-1})	19	47.3 ± 3.7
Predicted MAS (km·h^{-1})	19	15.0 ± 1.4
Time to exhaustion at 115% MAS (s)	19	181.5 ± 53.1
Yo-yo IR2 (m)	19	689 ± 155

MAOD = maximum accumulated oxygen deficit, MAS = maximum aerobic speed.

These results show significant relationships between yo-yo IR2 performance and $\dot{V}O_{2max}$ ($r = 0.62$, $p = 0.005$), relative aerobic intensity (%$\dot{V}O_{2max}$ at 12.5 km·h^{-1}) ($r = -0.72$, $p = 0.001$) and predicted MAS ($r = 0.70$, $p = 0.001$). When separated into high and low yo-yo IR2 groups there was a significant difference in $\dot{V}O_{2max}$, relative aerobic intensity and predicted MAS (Table 5.3).

Table 5.2: The relationships between variables are identified with Pearson's correlation coefficients.

		MAOD	Relative aerobic intensity	Running Economy	Predicted MAS	Yo-yo IR2 (m)
$\dot{V}O_{2max}$ (mL·kg·min^{-1})	**r**	.70	-.70	.48	.54	.62
	p	.001	.001	.04	.02	.005
MAOD (mL O_2 eq·kg·min^{-1})	**r**		-.22	.66	.04	.16
	p		.36	.002	.89	.50
Relative aerobic intensity	**r**			.29	-.91	-.72
(%$\dot{V}O_{2max}$ at 12.5 km·h^{-1})	**p**			.22	.00	.001
Running Economy (VO_2 mL·kg·min^{-1}at 12.5 km·h^{-1})	**r**				-.40	-.05
	p				.09	.86
Predicted MAS (km·h^{-1})	**r**					.70
	p					.001

MAOD = maximal accumulated oxygen deficit, MAS = maximal aerobic speed.

Table 5.3: The difference between variables when separated into high (n = 8) and low (n = 11) yo-yo IR2 scores.

	High yo-yo IR2	Low yo-yo IR2	Difference in mean	P value
$\dot{V}$**O_{2max}** (mL·kg·min^{-1})	60.13 ± 4.3	53.93 ± 5.66	6.2 (1.1 – 11.3)	0.02
MAOD (mL O_2 eq·kg·min^{-1})	15.55 ± 6.71	12.43 ± 5.26	3.1 (-2.7 – 8.9)	0.27
Relative aerobic intensity (%$\dot{V}O_{2max}$ at 12.5 km·h^{-1})	78.93 ± 4.57	87.92 ± 7.83	-9.0 (-15.5 – -2.4)	0.01
Running Economy (VO_2 mL·kg·min^{-1}at 12.5 km·h^{-1})	47.39 ± 3.43	47.16 ± 4.1	0.22 (-3.5 – 4.0)	0.9
Predicted MAS (km·h^{-1})	15.84 ± 1.23	14.38 ± 1.24	1.5 (0.24 – 2.7)	0.02

Mean ± SD are displayed and 95% confidence limits are represented in parentheses. MAOD = maximal accumulated oxygen deficit, MAS = maximal aerobic speed.

Figure 5.1 displays partial correlation analysis revealing that when controlled for $\dot{V}O_{2max}$ and relative aerobic intensity predicted MAS is not significantly related to yo-yo IR2 performance (r = 0.28, p = 0.28). The relationship between $\dot{V}O_{2max}$ and relative aerobic intensity was maintained when controlled by predicted MAS (r = -0.6, p =0.01). MAOD was significantly correlated with $\dot{V}O_{2max}$ even when controlling for running economy (r = 0.57, p = 0.01). Running economy was no longer significantly correlated with $\dot{V}O_{2max}$ when controlling for MAOD (r = 0.04, p = 0.87).

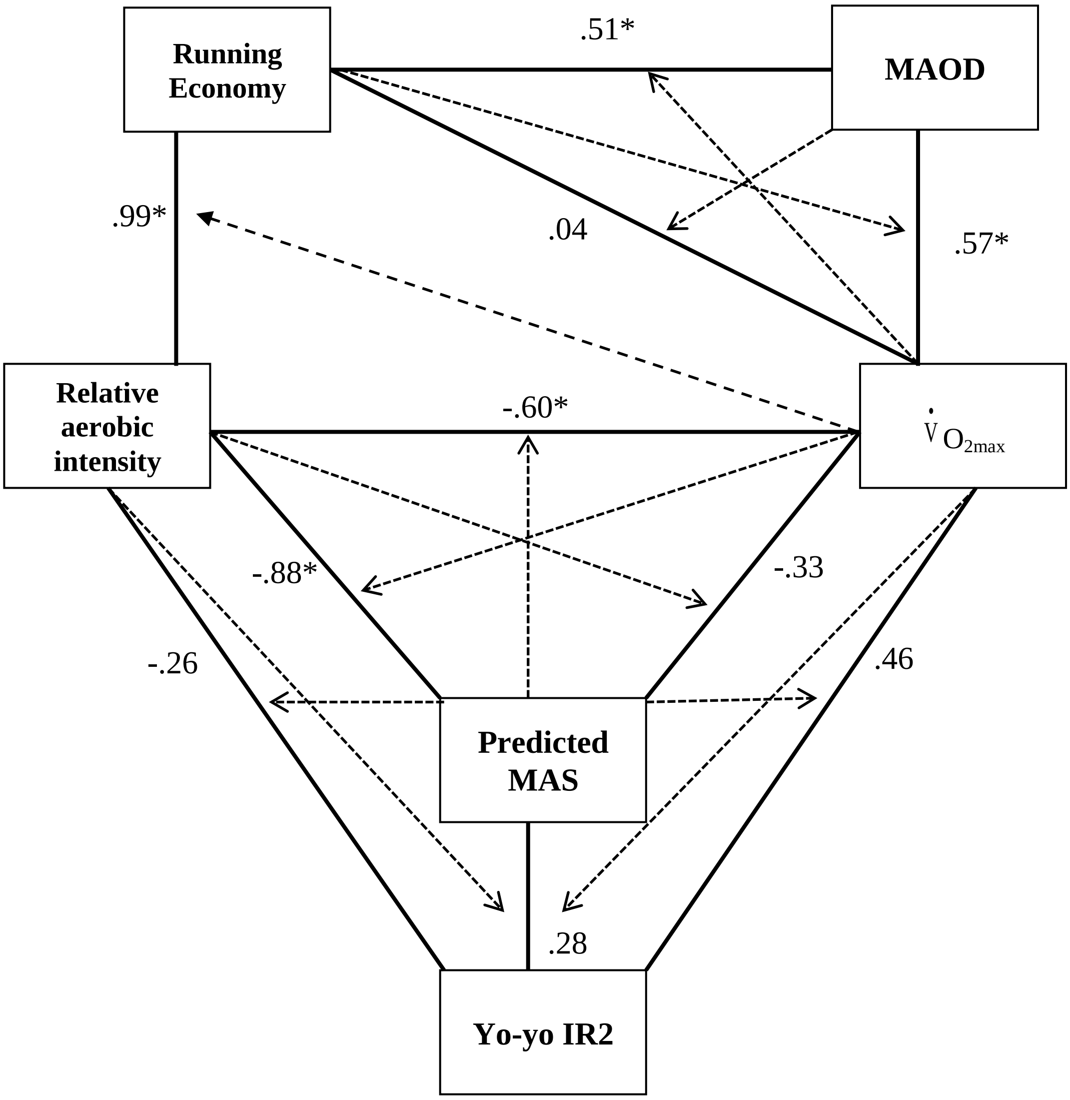

Figure 5.1: Partial correlation matrix showing the interaction between variables when controlling for other related variables. The solid lines represent the variables being correlated, whilst the dotted arrows represent the variable being controlled for in the correlation. Pearson's correlation coefficients are represented in this figure with significance at the 0.05 level shown by asterix.

Discussion

The aim of this study was to identify the physiological factors associated with yo-yo IR2 performance. The main findings of this study are predicted MAS and relative aerobic intensity provide the greatest total associations with yo-yo IR2. Furthermore, when separated into high and low yo-yo IR2 groups only predicted MAS, relative aerobic intensity and $\dot{V}O_{2max}$ were significantly different between groups. However, predicted MAS was no longer significantly correlated with yo-yo IR2 when controlled for $\dot{V}O_{2max}$ and relative aerobic intensity. Neither $\dot{V}O_{2max}$ nor relative aerobic intensity was significantly correlated with yo-yo IR2 performance when predicted MAS was controlled.

To the authors knowledge this is the first study to identify the association between predicted MAS and relative aerobic intensity from a sub-maximal speed with yo-yo IR2 performance (Table 5.2). Both of predicted MAS and relative aerobic intensity showed large correlations with yo-yo IR2 performance. $\dot{V}O_{2max}$ was also significantly correlated with yo-yo IR2 performance. Previous studies have found a moderate correlation between $\dot{V}O_{2max}$ and yo-yo IR2 score ($r = 0.58$)[13] which is similar to the current study ($r = 0.62$). Furthermore, when separated into high and low yo-yo IR2 groups predicted MAS, relative aerobic intensity and $\dot{V}O_{2max}$ were significantly different ($p = 0.02$, 0.02 and 0.01 respectively). Previous training studies have demonstrated improvements in $\dot{V}O_{2max}$ were simultaneously observed with improvements in yo-yo IR1 test performance[22, 23]. Interestingly Ferrari Bravo et al. observed improvements in repeated sprint ability simultaneously with improvements in $\dot{V}O_{2max}$ and yo-yo IR1 performance[23]. Repeated sprint ability has shown only moderate correlations with $\dot{V}O_{2max}$ and is often dictated by the number of repetitions and duration of the test[24-26]. In agreement with previous results the current study demonstrates aerobic power to be a dominate contributor to yo-yo IR2 performance.

This study identified that predicted MAS, relative aerobic intensity and $\dot{V}O_{2max}$ are inter-related (Table 5.2). The results of the partial correlation analysis depicts that when these variables were isolated (controlled for other significantly related variables) none of them were significantly correlated with yo-yo IR2 performance. However, $\dot{V}O_{2max}$ showed a trend towards a relationship with yo-yo IR2 ($r = 0.46$, $p = 0.09$). This is the first study to identify the direct association between predicted MAS, relative aerobic intensity and yo-yo IR2 performance. Furthermore, running economy and MAOD showed indirect influences to yo-yo IR2 performance by correlating with $\dot{V}O_{2max}$ and relative aerobic intensity in isolation. This finding maybe explained by the homogeneity of the participants such that those participant with a greater $\dot{V}O_{2max}$ so happened to have a greater MAOD.

The current study also identifies a clear overlap of physiological abilities that contribute to the yo-yo IR2 performance. These results identify the likely adaptations that will occur when improving yo-yo IR2 performance and may assist coaches in identifying strengths and weaknesses in the individual athletes.. Identifying the differences in individual physiological profiles allows coaches to design more specific training programs. One example of two athletes with different physiological profiles from the current data set is: two participants which had the same yo-yo IR2 performance (680 m), also had a similar predicted MAS; participant A 16.4 km·h^{-1}, participant B 16.0 km·h^{-1} (~2% difference). However, participant A had a much lower $\dot{V}O_{2max}$ (56.5 vs. 62.3 mL·kg·min^{-1}, ~9% difference). Interestingly, participant A appeared to compensate for a weaker $\dot{V}O_{2max}$ by having a superior running economy (43.7 vs. 49.0 mL·kg·min^{-1}, ~11% difference). Future research may try and identify how athletes obtain different physiological profiles yet obtain the same performance outcomes.

Although the current study measured aerobic power and estimated anaerobic capacity it should be recognised that the high speed/acceleration nature of the yo-yo IR2 test may require a contribution of other unmeasured capacities such as: leg power, speed, agility and acceleration[12]. Previously physical qualities such as MAS, $\dot{V}O_{2max}$, agility, 5 m and 10 m sprint times are moderately correlated with the yo-yo intermittent endurance (level 2) test[12]. Furthermore, post-test muscle biopsies indicate a reduction in muscle phosphate creatine levels after the completion of the yo-yo IR2 test[9]. Further research should focus on identifying the relative contribution of these qualities to the yo-yo IR2 test for a more complete picture of the physiological requirements of the yo-yo IR2 test and thus team sport performance.

Conclusion

This novel analysis of the physiological contributors to the yo-yo IR2 identified there are overlapping physical traits that comprise yo-yo IR2 performance with the most dominant being $\dot{V}O_{2max}$, predicted MAS and relative aerobic intensity. Furthermore, these variables may be influenced by other variables such as VO_2 utilisation at sub-maximal speed and MAOD.

Practical Implications

- Yo-yo IR2 performance are derived from a complex interaction of variables, but are mostly related to aerobic qualities such as $\dot{V}O_{2max}$, MAS and relative aerobic intensity.
- Physiological testing aimed at determining the athletes underlying limitations to yo-yo IR2 performance should be conducted to enable greater specificity of training.

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References

1. Dawson B, Hopkinson R, Appleby B, Stewart G, Roberts C. Player movement patterns and game activities in the Australian Football league. Journal of Science and Medicine in Sport. 2004;7(3):278-91.
2. Rampinini E, Impellizzeri FM, Castagna C, Coutts A, Wisloff U. Technical performance during soccer matches of the Italian Sere A league: Effect of fatigue and competitive level. Journal of Science and Medicine in Sport. 2009;12(1):227-33.
3. Lorenzen CL, Williams MD, Turk P, Meehan DL, Cicioni Kolsky DJ. Relationship between velocity reached at VO2max and time trial performance in elite Australian rules footballers. International Journal of Sports Physiology and Performance. 2009;4:408-11.
4. Mooney MG, Hunter JR, O'Brien B J, Berry JT, Young WB. Reliability and Validity of a Novel Intermittent Peak Running Speed Test for Australian Football. Journal of Strength and Conditioning Research. 2011;25(4):966-79.
5. Young W, Prior L. Relationship between pre-season anthropometric and fitness measures and indicators of playing performance in elite junior Australian Rules football. Journal of Science and Medicine in Sport. 2007;10:110-8.
6. Veale JP, Pearce AJ, Carlson JS. The Yo-Yo Intermittent Recovery Test (Level 1) to discriminate elite junior Australian football players. Journal of Science and Medicine in Sport. 2010; 13(3):329-31.
7. Mooney M, O'Brien B, Cormack S, Coutts A, Berry J, Young W. The relationship between physical capacity and match performance in elite

Australian football: A mediation approach. Journal of Science and Medicine in Sport. 2011;14(5):447-52.

8. Castagna C, Impellizzeri FM, Cecchini E, Rampinini E, Alverez JCB. Effect of intermittent-endurance fitness on match performance in young male soccer players. Journal of Strength and Conditioning Research. 2009;23(7):1954-9.
9. Krustrup P, Mohr M, Amstrup T, Rysgaard T, Johansen J, Steensberg A, et al. The yo-yo intermittent recovery test: physiological response, reliability, and validity. Medicine and Science in Sports and Exercise. 2003;35(4):697-705.
10. Rampinini E, Sassi A, Azzalin A, Castagna C, Menaspa P, Carlomagno D, et al. Physiological determinants of Yo-Yo intermittent recovery tests in male soccer players. European Journal of Applied Physiology. 2010;108(2):401-9.
11. Thomas A, Dawson B, Goodman C. The Yo-Yo test: Reliability and association with a 20-m shuttle run and VO2max. International Journal of Sports Physiology and Performance. 2006;1:137-49.
12. Brito J, Fernandes L, Seabra A, Rebelo A. Factors influencing the performance of young football players in the yo-yo intermittent endurance test (Level 2). Biomedical Human Kinetics. 2010;2:51-3.
13. Bangsbo J, Iaia FM, Krustrup P. The yo-yo intermittent recovery test: A useful tool for evaluation of physical performance in intermittent sports. Sports Medicine. 2008;38(1):37-51.
14. Krustrup P, Mohr M, Nybo L, Jensen JM, Nielsen JJ. The yo-yo IR2 test: Physiological response, reliability, and application to elite soccer. Medicine & Science in Sport & Exercise. 2006;38(9):1666-73.

15. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. Journal of Sports Sciences. 1996;14(4):321-7.
16. Spencer MR, Gastin PB. Energy system contribution during 200- to 1500-m running in highly trained athletes. Medicine and Science in Sports and Exercise. 2001;33(1):157-62.
17. Bangsbo J, Gollnick PD, Graham TE, Juel C, Kiens B, Mizuno M, et al. Anaerobic energy production and O2 deficit-debt relationship during exhaustive exercise in humans. Journal of Physiology. 1990;422:539-59.
18. Roberts AD, Clark SA, Townsend NE, Anderson ME, Gore CJ, Hahn AG. Changes in performance, maximal oxygen uptake and maximal accumulated oxygen deficit after 5, 10 and 15 days of live high:train low altitude exposure. European Journal of Applied Physiology. 2003;88(4-5):390-5.
19. Hale T. History of developments in sport and exercise physiology: A. V. Hill, maximal oxygen uptake, and oxygen debt. Journal of Sports Science. 2008;26(4):365-400.
20. Gastin PB, Lawson DL. Influence of training status on maximal accumulated oxygen deficit during all-out cycle exercise. European Journal of Applied Physiology and Occupational Physiology. 1994;69(4):321-30.
21. Hamby DM. A review of techniques for parameter sensitivity analysis of environmental models. Environmental Monitoring and Assessment. 1994;32:135-54.
22. Impellizzeri FM, Rampinini E, Muffiuletti NA, Castagna C, Bizzini M, Wisloff U. Effects of aerobic training on the exercise-induced decline in short-

passing ability in junior soccer players. Applied Physiology, Nutrition and Metabolism. 2008;33:1192-8.

23. Ferrari Bravo D, Impellizzeri FM, Rampinini E, Castagna C, Bishop D, Wisloff U. Sprint vs. interval training in football. International Journal of Sports Medicine. 2008;29(8):668-74.
24. Spencer M, Bishop D, Dawson B, Goodman C. Physiological and metabolic responses of repeated-sprint activities:specific to field-based team sports. Sports Medicine. 2005;35(12):1025-44.
25. Hunter JR, O'Brien B J, Mooney MG, Berry J, Young WB, Down N. Repeated Sprint Training Improves Intermittent Peak Running Speed in Team-Sport Athletes. Journal of Strength and Conditioning Research. 2011;25(5):1318-25.
26. Tomlin DL, Wenger HA. The relationship between aerobic fitness, power maintenance and oxygen consumption during intense intermittent exercise. Journal of Science and Medicine in Sport. 2002;5(3):194-203.

Chapter 6:
Does Physical Capacity and Interchange Rest Periods Influence the Match Exercise Intensity Profile During Australian Football Matches?

Abstract

Purpose: The purpose of this study was to identify if yo-yo intermittent recovery (level 2) (yo-yo IR2) and the number of interchange rotations affected the match activity profile of elite Australian Footballers.

Method: Fifteen elite Australian Footballers completed the yo-yo IR2 prior to the beginning of the season and played in 43 matches where match activity profiles were measured via micro technology devices containing a global positioning system (GPS) and accelerometer. An interchange rotation was counted when a player left the field and was replaced with another player. Yo-yo IR2 results were further split into *high* and *low* groups to distinguish the effect of interchange rotations on fit and less fit players.

Results: Players match speed decreased from first to fourth quarter, whilst mean speed ($m \cdot min^{-1}$: $p = 0.05$) and low intensity activity (LIA, <15 $km \cdot h^{-1}$) per minute (LIA $m \cdot min^{-1}$) ($p = 0.06$) significantly decreased in the second half. Yo-yo IR2 influenced the amount of $m \cdot min^{-1}$, high intensity running (HIR, >15 $km \cdot h^{-1}$) per minute (HIR $m \cdot min^{-1}$) and Accelerometer Load™·min^{-1} (Load™·min^{-1}) throughout the entire match ($p < 0.01$). The number of interchanges significantly affected the HIR $m \cdot min^{-1}$and $m \cdot min^{-1}$ throughout the match except the second quarter. Furthermore, the low yo-yo IR2 group had significantly lower LIA $m \cdot min^{-1}$ in the fourth quarter compared to the high yo-yo IR2 group (92.2 v. 96.7 $m \cdot min^{-1}$, $p = 0.06$).

Conclusions: Both the yo-yo IR2 and number of interchanges contribute to $m \cdot min^{-1}$ and HIR $m \cdot min^{-1}$ produced by elite Australian Footballers, affecting their match activity. However, whilst it appears that improved yo-yo IR2 performance prevents reductions in LIA $m \cdot min^{-1}$ during a match, higher speed activities (HIR $m \cdot min^{-1}$) and overall physical activity ($m \cdot min^{-1}$ and Load·min^{-1}) is still reduced.

Key Words: yo-yo intermittent recovery test, substitution, high speed running.

Introduction

Australian football is a field-based team sport that requires high-intensity, intermittent exercise, including many intense activities (i.e. accelerations, decelerations, tackling, collisions, sprinting, change of direction etc.). These match demands elicit high levels of fatigue in players which have been shown through reductions in player activity profiles[1, 2]. Whilst it is generally understood that many factors influence performance in Australian Football (i.e. player quality, tactical strategy, skill execution etc.), a major focus for most teams is to develop physical capacities and tactical systems that provide their players with the capacity to maintain higher exercise intensities towards the end of the game. Two of the obvious methods for achieving this are improving the physical capacity of players through specific training and employing tactical strategies such as using player interchange to provide regular recovery opportunities during matches. However, despite the general assumption that both approaches contribute to improved physical performance, to date, there has been little scientific evidence examining the relationships between player's physical capacity and player interchange on match activity profiles in elite Australian Football.

Several studies have shown that player match activity profiles are reduced as Australian Football matches progress and players accumulate fatigue[1-3]. For example, Coutts et al.[1] reported a large reduction in both overall match speed and higher speed running (> 14.4 km·h^{-1}) from the first to the fourth quarters of matches in professional Australian Football players from a team ranked in the bottom 25% of the competition. In addition, it was also reported that players reduced their exercise lower intensity activities as the matches progressed, possibly as a form of pacing to retain the ability to exercise at higher intensities when required to. More recently, Aughey et al.[3] reported a moderate reduction in the number of maximal accelerations (efforts 2.78-10.00 $m \cdot s^{-2}$) and a small reduction in the distances travelled at higher speeds (>14.9 $km \cdot h^{-1}$) during professional Australian Football matches. However, in contrast to the earlier study[1], these investigators did not observe any changes in the activity profile at lower speeds, and it was suggested that improved physical capacities of the players in the higher ranked team explained these differences. Unfortunately however, the fitness characteristics of these two teams were not reported and analysis of this suggestion is not possible. Whilst it is tempting to speculate improved fitness characteristics affect the match activity profile of professional Australian Football players, at present the relationship between specific fitness qualities on the match activity profile of professional Australian Football player's remains unclear.

Much of the focus of physical training in professional Australian Football players is on the development of specific fitness capacities that allow improved physical performance during competition, which is based on the findings from both Australian Football and soccer that HIR is associated with improved performance[4, 5]. For example, it has recently been demonstrated that professional Australian Football players who performed better on the yo-yo intermittent recovery (level 2) test (yo-yo IR2) had an increased ability to gain more disposals of the ball during matches and this was mediated through increased high speed running (HIR, >15 $km \cdot h^{-1}$)[4] during matches. These results suggest that focussing on improving the match specific characteristics (seen when performing the yo-yo IR2 performance) of professional Australian Football can improve a player's ability to become involved in the play. However, the direct relationship between improved physical capacity and improved playing performance is less clear, as other researchers have shown that higher calibre Australian Football players had lower physical activity profile during matches but increased involvement with ball (i.e. kicks, handballs, total disposals) than lower calibre players within the same Australian Football team[6]. Collectively, the findings from these studies demonstrate that whilst the capacity to complete HIR is important to increase the number of disposals during Australian Football, a high overall match speed itself is not as important as the player's ability to gain possession of the ball. However, the relationship between physical capacity and physical activity during Australian Football matches is currently not clear. It may be that having the capacity to perform higher speed activities throughout matches is an important characteristic for improved match performance in Australian Football.

Over the past decade, there has been an increased use of the interchange bench as a tactical strategy to manage player work demands and to provide players with opportunities for rest to cope with the increasing running demands of the sport. In 2003, teams made fewer than 30 player interchanges during games, but greater than 120 interchanges per game in 2011 despite rule modifications attempting to limit its use (Unpublished observations, Champion Data©, South Bank, Australia). Depending on position within a team, players are now usually provided 0 – 10 interchanges per game for a mean duration of 3.5±1.5 mins (ranging from 43 s to 8.5 min each) in addition to the quarter time, three quarter time and half-time breaks (unpublished observation, 2010). These breaks provide increased opportunities for fluid, electrolyte and carbohydrate ingestion and passive rest which may delay fatigue and increase the capacity for higher intensity exercise[7, 8]. It is widely considered that the increase in frequency of rest periods during matches has contributed to the increased physical activity profiles presently observed in Australian Football. At present however, there have been no published studies that have examined the associations between player interchange and physical activity outputs in professional Australian Football. Therefore the purpose of this study was to identify if there is evidence of reduced exercise intensity across Australian Football matches and to identify if physical capacity (i.e. yo-yo IR2) or the number or interchange rotations impact match exercise intensity.

Methods

Fifteen elite Australian footballers from the same team participated in this study. The players had a mean ± standard deviation (SD) stature of 186.1 ±6.5 cm, mass of 84.3 ±8.3 kg and age of 22.6 ±3.2 years. Informed consent was gathered prior to the commencement of the studies. Ethical approval was obtained by the University Research Ethics Committee.

This study is a longitudinal analysis across an entire 22 match elite Australian Football League (AFL) season. Participants were required to perform the yo-yo IR2 less than 10 days prior to the first match of the regular season. All participants performed the test on the same indoor surface. Each participant had completed this test previously and was familiar with the procedures. This procedure has been described in detail elsewhere with typical errors ranging from 4.9−10.4% for a variety of sports and standards[9]. The players were then allocated into high and low groups on the basis of yo-yo IR2 using median split technique. After the test, participants underwent one week of their regular training before the commencement of the season.

All participants had their match activity profiles recorded by a portable GPS unit sampling at 5 Hz whilst the internal accelerometer (housed inside the same GPS device) sampled at 100 Hz (MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia). Match activity profiles were gathered throughout the entire 22 match season. Each player recorded between 1 – 4 match profiles for the season. Global positioning system and accelerometer data was downloaded post match using manufacturer specific software (Logan Plus v. 4.4.0) for analysis.

Variables collected from GPS were distance travelled per minute ($m \cdot min^{-1}$), distance travelled at HIR per minute (HIR $m \cdot min^{-1}$) where HIR m =distance travelled >15 $km \cdot h^{-1}$, lower speed activity (LIA) distance travelled <15 $km \cdot h^{-1}$ per minute, HIR as a percentage of total distance (%HIR), and accelerometer Load™$\cdot min^{-1}$ as described previously[4]. These variables have been tested for reliability and validity; HIR activities (striding and sprinting, coefficient of variation (CV) = 9.0–11.9% (activity dependent), validity range -6.2–4.6% (activity dependent)[10] whilst Load™$\cdot min^{-1}$ has shown a CV of <2%[11]. The number of interchanges (substitutions) that occurred per player was recorded as the number of times the player was not participating as one of the active 18 players on the field. Rotations were done mostly ad libitum and were controlled by the head coach. However, players would wait until an appropriate opportunity during the match to rotate i.e. when play was near the dedicated interchange area or a goal had been scored.

One-way analysis of variance (ANOVA) was performed to determine the time effect (difference between quarters) of all match exercise intensity variables. A two-way ANOVA was performed to identify effects by quarter and by capacity (yo-yo IR2).

Multiple regression analysis was performed with yo-yo IR2 and number of interchanges used to predict match intensity variables for all four quarters. Tukey's post hoc analysis was performed to identify significant differences between conditions. Multiple regression and ANOVA's were performed on Statistica version 7.0 with significance set at the 0.1 level. This significance level was chosen as <0.05 significance criteria may be too conservative for detecting important practical changes in the elite sport environment[4, 12]. All data are presented as mean ± SD unless otherwise stated.

Results

The mean (± SD) Yo-yo IR2 (n = 43) was 1029 ± 185 m with the median split occurring at 1040 m, the mean (± SD) of the number of interchange rotations for each quarter were Q1 = 1.4 ± 0.6, Q2 = 1.4 ± 0.7, Q3 = 1.2 ± 0.6, Q4 = 1.3 ± 0.7 respectively. There was no significant difference in time on the field for any quarter (Q1 = 23.8 ± 8.1, Q2 = 24.1± 7.1, Q3 = 23.8 ± 5.4, Q4 = 25.9 ± 4.0 minutes respectively). Changes in match activity measures between quarters and halves showed significant differences between the first quarter and fourth quarters ($m \cdot min^{-1}$, HIR $m \cdot min^{-1}$ and LIA $m \cdot min^{-1}$), and first and second half ($m \cdot min^{-1}$ and LIA $m \cdot min^{-1}$) (See Table 6.1). The weighting of the variables is presented in Table 6.2 in a multiple regression analysis and indicates the relative importance of the variable in predicting the match exercise intensity variables across the match.

Table 6.1: Mean (90% Confidence limits) match activity measures for each quarter.

	Q1	Q2	Q3	Q4	1st half	2nd half
$m \cdot min^{-1}$	141.9 (137.3 – 146.5)	133.7 (129.1 – 138.3)	134.9 (131.3 – 139.5)	129.8 † (125.2 – 134.4)	137.8 (134.5 – 141.1)	132.3* (129.1 – 135.6)
HIR $m \cdot min^{-1}$	42.5 (39.2 – 45.9)	37.7 (34.4 – 41.0)	39.2 (35.9 – 42.5)	35.1 † (31.8 – 38.3)	40.1 (37.8 – 42.5)	37.1 (34.8 – 39.5)
LIA $m \cdot min^{-1}$	99.4 (97.2 – 101.6)	96.0 (93.8 – 98.2)	95.8 (93.5 – 98.0)	94.7 † (92.5 – 96.9)	97.7 (96.2 – 99.3)	95.2 * (93.7 – 96.8)
%HIR	29.0 (27.3 – 30.7)	27.3 (25.6 – 28.9)	28.1 (26.4 – 29.8)	26.0 (24.4 – 29.8)	28.1 (26.9 – 29.2)	27.1 (25.8 – 28.2)
Load™$\cdot min^{-1}$	16.3 (15.5 – 17.1)	15.3 (14.5 – 16.1)	15.9 (15.1 – 16.8)	15.1 (14.2 – 15.8)	15.8 (15.2 – 16.4)	15.5 (14.9 – 16.1)

† represents significant difference from 1st quarter at the 0.1 level, ***** represents significant difference from 1st half at the 0.1 level.

The greatest differences in all match exercise intensity indices were between the first and fourth quarters significant differences were observed in m·min^{-1} ($p = 0.01$),HIR m·min^{-1} ($p = 0.04$) and LIA m·min^{-1} ($p = 0.06$). Only m·min^{-1} and LIA m·min^{-1} were significantly reduced in the second half in the pooled sample (see Table 6.1). When participants were separated into "high" ($n = 24$) and "low" ($n = 19$) yo-yo IR2 scores, significant differences were observed in m·min^{-1}, HIR m·min^{-1}, LIA m·min^{-1} and %HIR in the first quarter and fourth quarter (all variables $p < 0.01$ respectively) (Figure 6.1). Furthermore, LIA m·min^{-1} and Load™·min^{-1} were significantly different between high and low yo-yo IR2 groups in the fourth quarter only ($p = 0.04$ and $p < 0.01$ respectively). Specifically, HIR m·min^{-1} was reduced in the fourth quarter compared to the first quarter for the *high* yo-yo IR2 group whilst the *low* yo-yo IR2 group did not significantly change. However, LIA m·min^{-1} in the *low* yo-yo IR2 group significantly reduced in the fourth quarter compared to the first quarter whilst it remained constant in the *high* yo-yo IR2 group.

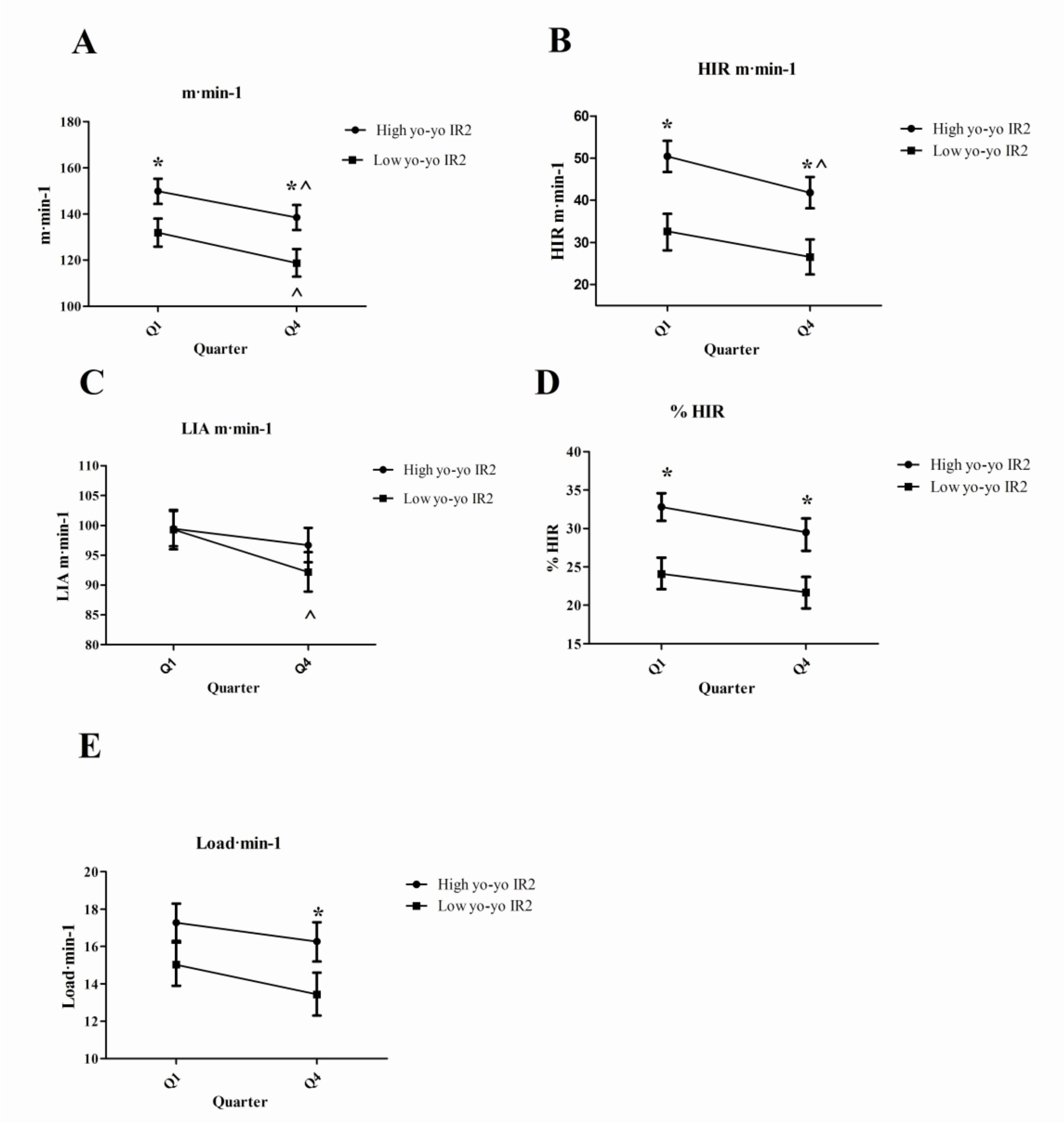

Figure 6.1: All graphs identify the difference between 1st and 4th quarters (Q1 & Q4) when separated into high and low Yo-yo IR2 score **A -** m·min^{-1}, **B –** high intensity running (HIR) m·min^{-1}, **C –** low intensity activity **(**LIA) m·min^{-1}, **D -** % HIR, **E -** load·min^{-1}. The graphs represent means and error bars represent 90% confidence limits. * represents significant difference at the 0.1 level between high and low groups whilst ^ represents significant at the 0.1 level difference between Q1 and Q4.

Multiple regression analysis showed that yo-yo IR2 performance and number of interchanges both showed significant contribution to m·min^{-1}, HIR m·min^{-1} and %HIR for all four quarters, with the exception of the second quarter where the number of interchanges was not significantly related (Table 6.2). Yo-yo IR2 score was significantly related to Load™·min^{-1} throughout the entire match, whilst the number of interchanges were only related in the third and fourth quarters. The number of interchanges did not relate to LIA m·min^{-1} during any quarter. However, yo-yo IR2 significantly contributes to LIA m·min^{-1} in the second and fourth quarters.

Table 6.2: Multiple regression analysis identifying the weight and relationship Yo-yo IR2 and number of interchange has to the dependant variable per quarter.

Dependant Variable	Independent Variables	Q1 β	Q1 partial r	Q1 p-value	Q2 β	Q2 partial r	Q2 p-value	Q3 β	Q3 partial r	Q3 p-value	Q4 β	Q4 partial r	Q4 p-value
	Yo-yo IR2	0.55 ± 0.10	0.52	<0.01	0.55 ± 0.10	0.56	<0.01	0.54 ± 0.10	0.54	<0.01	0.67 ± 0.10	0.72	<0.01
m·min^{-1}	No. interchanges	0.40 ± 0.10	0.64	<0.01	0.17 ± 0.10	0.21	0.19	0.31 ± 0.10	0.31	0.01	0.29 ± 0.1	0.41	0.01
HIR	Yo-yo IR2	0.63 ± 0.10	0.74	<0.01	0.62 ± 0.10	0.64	<0.01	0.66 ± 0.10	0.71	<0.01	0.71 ± 0.10	0.79	<0.01
m·min^{-1}	No. interchanges	0.40 ± 0.10	0.58	<0.01	0.19 ± 0.10	0.24	0.12	0.33 ± 0.10	0.45	<0.01	0.34 ± 0.10	0.52	<0.01
LIA	Yo-yo IR2	0.11 ± 0.20	0.12	0.47	0.27 ± 0.20	0.27	0.08	0.13 ± 0.20	0.13	0.42	0.37 ± 0.10	0.37	0.02
m·min^{-1}	No. interchanges	0.20 ± 0.20	0.20	0.21	0.1 ± 0.20	0.10	0.53	0.14 ± 0.20	0.15	0.36	0.12 ± 0.10	0.13	0.42
	Yo-yo IR2	0.61 ± 0.10	0.70	<0.01	0.59 ± 0.10	0.60	<0.01	0.66 ± 0.10	0.72	<0.01	0.65 ± 0.10	0.72	<0.01
% HIR	No. interchanges	0.36 ± 0.10	0.49	<0.01	0.18 ± 0.10	0.23	0.14	0.38 ± 0.10	0.51	<0.01	0.35 ± 0.10	0.49	0.01
	Yo-yo IR2	0.47 ± 0.10	0.47	<0.01	0.40 ± 0.10	0.40	0.01	0.38 ± 0.10	0.41	0.01	0.36 ± 0.10	0.39	0.01
Load™·min^{-1}	No. interchanges	0.17 ± 0.10	0.19	0.20	0.18 ± 0.10	0.19	0.22	0.39 ± 0.10	0.42	0.01	0.37 ± 0.10	0.40	0.01

β = beta weight ± SE, No. interchanges = number of interchanges, HIR = high intensity running, LIA = low intensity activity, Q1 = quarter 1.

Discussion

This study aimed to determine the degree of change in activity profile during elite Australian Football matches and identify the influence of yo-yo IR2 performance and number of player interchanges on this profile. The major findings of this study were; 1) there was a significant reduction in $m \cdot min^{-1}$, HIR $m \cdot min^{-1}$ and LIA $m \cdot min^{-1}$ from the first to fourth quarters, 2) both yo-yo IR2 and the number of interchange rotations affect the activity profile of players throughout the match with yo-yo IR2 having the greater influence, 3) higher yo-yo IR2 performance has a fatigue sparing ability from 1st to 4th quarter, the high yo-yo IR2 group performed significantly more $m \cdot min^{-1}$ and HIR $m \cdot min^{-1}$ across the match and the low yo-yo IR2 group performed significantly less LIA in the 4th quarter.

The present results agree with previous research that reported a reduction in match exercise intensity measures across Australian Football matches[1, 13]. In particular, we observed that both LIA $m \cdot min^{-1}$ and HIR $m \cdot min^{-1}$ were significantly reduced in the fourth quarter compared to the first quarter ($p = 0.02$ and 0.01 respectively). However, the mean HIR $m \cdot min^{-1}$ did not significantly change in the second half, whereas the mean LIA $m \cdot min^{-1}$ was significantly reduced in the second half ($p = 0.06$). These findings are similar to others who found in comparison to the first quarter, distance travelled jogging (7–14.4 $km \cdot h^{-1}$) was significantly reduced as early as the second quarter, whilst distance at HIR (>14.4 $km \cdot h^{-1}$) was only significantly reduced in the fourth quarter[1]. These findings suggest that players may sacrifice distance travelled at low speed to compensate for the demands of high speed running as HIR $m \cdot min^{-1}$ has been linked with superior performance[4]. Furthermore, players with a greater yo-yo IR2 score were able to maintain the amount of LIA compared to those players with lower yo-yo IR2. Indeed, passive recovery allows for greater muscular PCr resynthesis in preparation for a high intensity effort, thus the amount of interchanges may also explain the differences in the literature[14]. Other factors such as movement patterns of the opposition, team tactics and match score may also have influenced the present results.

This study found the number of interchange rotations affected $m \cdot min^{-1}$, HIR $m \cdot min^{-1}$ and %HIR in the first, third and fourth quarters, whilst significantly influencing Load™$\cdot min^{-1}$ in the third and fourth quarter (see Table 6.2). Interestingly LIA $m \cdot min^{-1}$ was not influenced by the number of interchanges at any stage. This supports the above notion that a passive recovery assists the maintenance of HIR throughout an intermittent team sport but the passive recovery afforded by an interchange rotation appears to have little impact on LIA. Previous studies in soccer have identified that the substituting player performs more HIR than other players in the same position on the pitch[15]. Given that HIR $m \cdot min^{-1}$ is important to obtain ball disposals (particularly for nomadic players) the number of interchanges may be important (at least indirectly) to Australian Football performance[4]. To the authors' knowledge this is the first study in Australian Football to identify the influence of interchange rotations on match activity profile. Future research may focus on the optimal duration of interchanges to optimise recovery.

The present results revealed that the capacities assessed by the yo-yo IR2 are important qualities that are related to match activities in Australian Football, particularly in relation to $m \cdot min^{-1}$, HIR $m \cdot min^{-1}$, %HIR and Load™$\cdot min^{-1}$. Furthermore, yo-yo IR2 performance had a positive influence on LIA $m \cdot min^{-1}$ in the second and fourth quarters. This suggests that players with a lower yo-yo IR2 may rely on modifying their match activity profile to include more passive and or lower intensity active recovery on the field (e.g. walking or standing still) than players with a higher yo-yo IR2. These players may not be suited to being 'rested' on the field (e.g. midfielders rested in a forward or back pocket) and therefore require more frequent interchanges during the match.

This study also investigated if higher yo-yo IR2 performance provided any protection from a reduction in match locomotion during Australian Football. The $m \cdot min^{-1}$, HIR $m \cdot min^{-1}$, %HIR and Load™$\cdot min^{-1}$ showed a similar decline from first quarter to fourth quarter, demonstrating that yo-yo IR2 was unable to prevent a reduction in these match exercise intensity measures. It was also observed that LIA $m \cdot min^{-1}$ significantly declined from first to fourth quarter in the low yo-yo IR2 group, suggesting that a higher yo-yo IR2 performance may assist in the players' ability to maintain LIA during a match. This may allow players to: make position i.e. set up in a zone defence or cover an opponent, make more contests (such as ball-ups, throw-ins) more effectively. However, in agreement with previous research[1], the high yo-yo IR2 group did produce significantly greater $m \cdot min^{-1}$, HIR $m \cdot min^{-1}$, %HIR in both the first and fourth quarters whilst also having superior Load™$\cdot min^{-1}$, suggesting that the players with greater capacity produce more distance at high speeds yet are able to maintain the distance covered at lower speeds[1].

Conclusion

This study showed that Yo-yo IR2 score and the number of interchange rest periods during a quarter can influence the activity profile of Australian Football players. However, yo-yo IR2 score does not influence the change in HIR profile from first quarter to fourth quarter. These results agree with earlier research suggesting that professional Australian Football players spare the amount of HIR performed by reducing the LIA in the second half. Future studies should focus on the effect of football specific training on the activity profile of players and the effect of accumulative fatigue on the match activity profile in elite Australian Football.

Practical applications

- More robust planning can be done to ensure greater rotations to those who are susceptible to reduced match exercise intensity.
- Match exercise intensity is reduced in the fourth quarter but can be more controlled by having a high yo-yo IR2 score and high interchange frequency.
- Low speed activities provide coaches with a better insight into the coping abilities of the players with lower yo-yo IR2 scores.

Acknowledgments

There was no external funding provided by any organisation for this study.

References

1. Coutts AJ, Quinn J, Hocking J, Castagna C, Rampinini E. Match running performance in elite Australian Rules Football. *Journal of Science and Medicine in Sport.* 2010;13(5):543-8.
2. Duffield R, Coutts AJ, Quinn J. Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. *Journal of Strength and Conditioning Research.* 2009;23(4):1238-44.
3. Aughey RJ. Australian football player work rate: evidence of fatigue and pacing? *International Journal of Sports Physiology and Performance.* 2010;5(3):394-405.
4. Mooney M, O'Brien B, Cormack S, Coutts A, Berry J, Young W. The relationship between physical capacity and match performance in elite Australian football: A mediation approach. *Journal of Science and Medicine in Sport.* 2011;14(5):447-52.
5. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences.* 2003;21:519-28.
6. Johnston RJ, Watsford ML, Pine MJ, Spurrs RW, Murphy A, Pruyn EC. Movement Demands and Match Performance in Professional Australian Football. *International Journal of Sports Medicine.* 2011.dio: 10.1055/s-0031-1287798
7. Bilzon JL, Allsopp AJ, Williams C. Short-term recovery from prolonged constant pace running in a warm environment: the effectiveness of a

carbohydrate-electrolyte solution. *European Journal of Applied Physiology* 2000;82(4):305-12.

8. Buchheit M, Cormie P, Abbiss CR, Ahmaidi S, Nosaka KK, Laursen PB. Muscle deoxygenation during repeated sprint running: Effect of active vs. passive recovery. *International Journal of Sports Medicine.* 2009;30(6):418-25.
9. Bangsbo J, Iaia FM, Krustrup P. The yo-yo intermittent recovery test: A useful tool for evaluation of physical performance in intermittent sports. *Sports Medicine.* 2008;38(1):37-51.
10. Jennings D, Cormack S, Coutts AJ, Boyd L, Aughey RJ. The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International Journal of Sports Physiology and Performance.* 2010;5(3):328-41.
11. Boyd L, Ball K, Aughey RJ. The reliability of minimaxX accelerometers for measuring physical activity in Australian football. *International Journal of Sports Physiology and Performance.* 2011;6(3):311-21.
12. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance.* 2006;1(1):50-7.
13. Duffield R, Coutts A, Quinn J. Core temperature responses and match running performance during intermittent sprint condition in warm conditions. *Journal of Strength and Conditioning Research.* 2009;23(4):1238-44.
14. Spencer M, Bishop D, Dawson B, Goodman C, Duffield R. Metabolism and performance in repeated cycle sprints: active versus passive recovery. *Medicine and Science in Sports and Exercise.* 2006;38(8):1492-9.

15. Carling C, Espie V, Le Gall F, Bloomfield J, Jullien H. Work-rate of substitutes in elite soccer: a preliminary study. *Journal of Science and Medicine in Sport.* 2010;13(2):253-5.

16. Glaister M. Multiple sprint work: Physiological responses, mechanisms of fatigue and the influences of aerobic fitness. *Sports Medicine.* 2005;35(9):757-77.

17. Tomlin DL, Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Medicine.* 2001;31(1):1-11.

Chapter 7:
General Discussion and Future Directions

Summary of Results and Discussion

The aim of this project was to identify the contribution of physical parameters to elite Australian Football performance. In Chapter 2 the current knowledge of the physical and performance parameters were explored. The review of literature revealed that there was segmented knowledge of overall Australian Football performance. Desirable physical qualities have been investigated and notation studies completed. However, what remained unclear is if the physical qualities affected the on field performance of Australian Football or if this effect was directly influencing performance or linked into a larger self-organising system. Seemingly from a previously presented conceptual model created of soccer performance it was likely that the physical performance parameters acted in conjunction with tactical and technical performance to influence the match outcome i.e. winning teams would have a greater aggregate tactical, technical and physical performance[1]. In fact, some studies have found that winning teams in elite soccer competitions travel less distance[2]. This suggests that the teams at the elite level compensate for a lower physical performance by superior tactical and physical abilities.

Chapter 3 contained a study that identified that unlike the conceptual model presented for soccer, physical performance (HIR $m \cdot min^{-1}$) contributed to technical performance (number of ball disposals). This mediating relationship was also found to be subject to individual conditions such as playing experience and playing position. Interestingly, these findings identify that it is not possible that the aggregate of tactical, technical and physical performance could determine match outcome as physical performance was influencing technical performance. Therefore the relationship between tactical, technical and physical performance is more likely to be an active system where tactical, technical and physical performance all overlap to contribute to match outcome (See Figure 7.1).

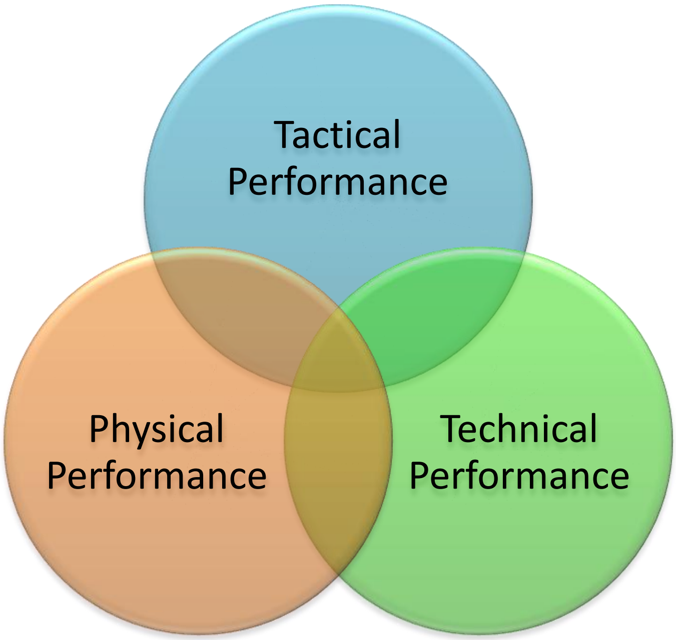

Figure 7.1: The interaction between tactical, technical and physical performance.

Chapter 4 introduces the influence of fatigue (specifically neuromuscular fatigue) to Australian Football performance. Previously neuromuscular fatigue has been shown to negatively correlate with coach's rating of performance[3]. Chapter 4 demonstrates that rather than having a direct influence on performance neuromuscular fatigue has a moderating effect on the interrelationship between coach's rating of performance and physical performance in particular Load·min^{-1}. This causes physical performance to disassociate from the coaches perceptions resulting in a less efficient performance system. The mechanisms for this disassociation are unclear based on the present data. However, our findings did also identify that the relationship between Load·min^{-1} and HIR m·min^{-1} was affected in fatigued players. Although very preliminary findings, it suggests that more research to identify changes in movement patterns of players in a fatigued state is warranted.

Chapter 5 investigated the contribution of physiological variables that influence the validated Australian Football field test (yo-yo IR2). Previous research has been conducted into the physical responses of athletes during and at completion of the yo-yo IR2 test[4]. However, results have been generalised to specific cohorts rather than an individual within the cohort. Chapter 5 aimed at identifying what the physiological interactions were that resulted in a higher yo-yo IR2 so these could be identified and trained on an individual basis. The results suggested that of the measures collected some had more weighting than other i.e. maximum aerobic speed, $\dot{V}O_{2max}$, and relative intensity. Interestingly, the results yielded several interrelationships that operated much like a self-organising system. The example given in Chapter 5 was of participant A having very different physiological characteristics than participant B yet resulted in the same yo-yo IR2 score. It was concluded that athletes are able to utilise their physical strengths (in light of their weaknesses) to perform the yo-yo IR2 test. What isn't clear is whether focusing training goals on the athlete's strengths or weaknesses will yield in greater improvements in field test performance. Future research may focus on the optimal individualise training program, based on improving strengths or weaknesses to maximise the adaptation.

Chapter 6 investigated the influence of tactical strategies and physical capacity, specifically interchange rotations and yo-yo IR2 score, on physical performance measures and match exercise intensity maintenance. A novel study in Australian

Football the results indicated the frequency of interchange rotations had a positive influence on physical performance throughout the match independent of the players physical capacity (yo-yo IR2 score). However, yo-yo IR2 had a greater weighting than interchange rotation frequency in predicting physical performance. Interestingly when analysed for reductions in match exercise intensity across the match high and low yo-yo IR2 groups had similar reductions from first to fourth quarter except for low intensity activity (LIA). The low yo-yo IR2 group had a sharper reduction in LIA than the higher yo-yo IR2 group who managed to maintain LIA across the match. These results indicate that higher physical capacity allowed players to travel further distances at a greater intensity in the first quarter but also maintain the LIA in the fourth quarter. In conjunction with having a greater physical capacity interchange rotations were found to influence the ratio of high intensity distance to low intensity distance travelled. This suggests that coaches can influence the match exercise intensity of their players during a match by altering the frequency of rotations. Currently it is unknown if the duration of interchanges or mode of recovery influences the subsequent match exercise intensity and helps maintain exercise intensity across an entire match.

The above results are all pieces to an overall Australian Football performance model that shows how physical performance interacts under difference conditions to tactical and technical performance. In piecing all these results together a larger conceptual model of performance is presented in Figure 7.1. Figure 7.1 shows how physical capacity of the athlete leads to a potentially greater match exercise intensity under the appropriate conditions (i.e. playing position and neuromuscular fatigue). It also shows that match exercise intensity contributes to tactical (coaches perception of performance) and technical performance (number of ball disposals) under the optimal conditions of playing position, fatigue status, and playing experience. This model visualises how physical, tactical and technical performance interact under a dynamic system that is adaptable to change and strategic manipulation (i.e. improving yo-yo IR2 performance or increasing interchange rotations).

There are many other components to Australian Football performance that are not presented in this thesis such as skill efficiency; however it provides a framework to build a much greater and comprehensive dynamic system (see Appendix C).

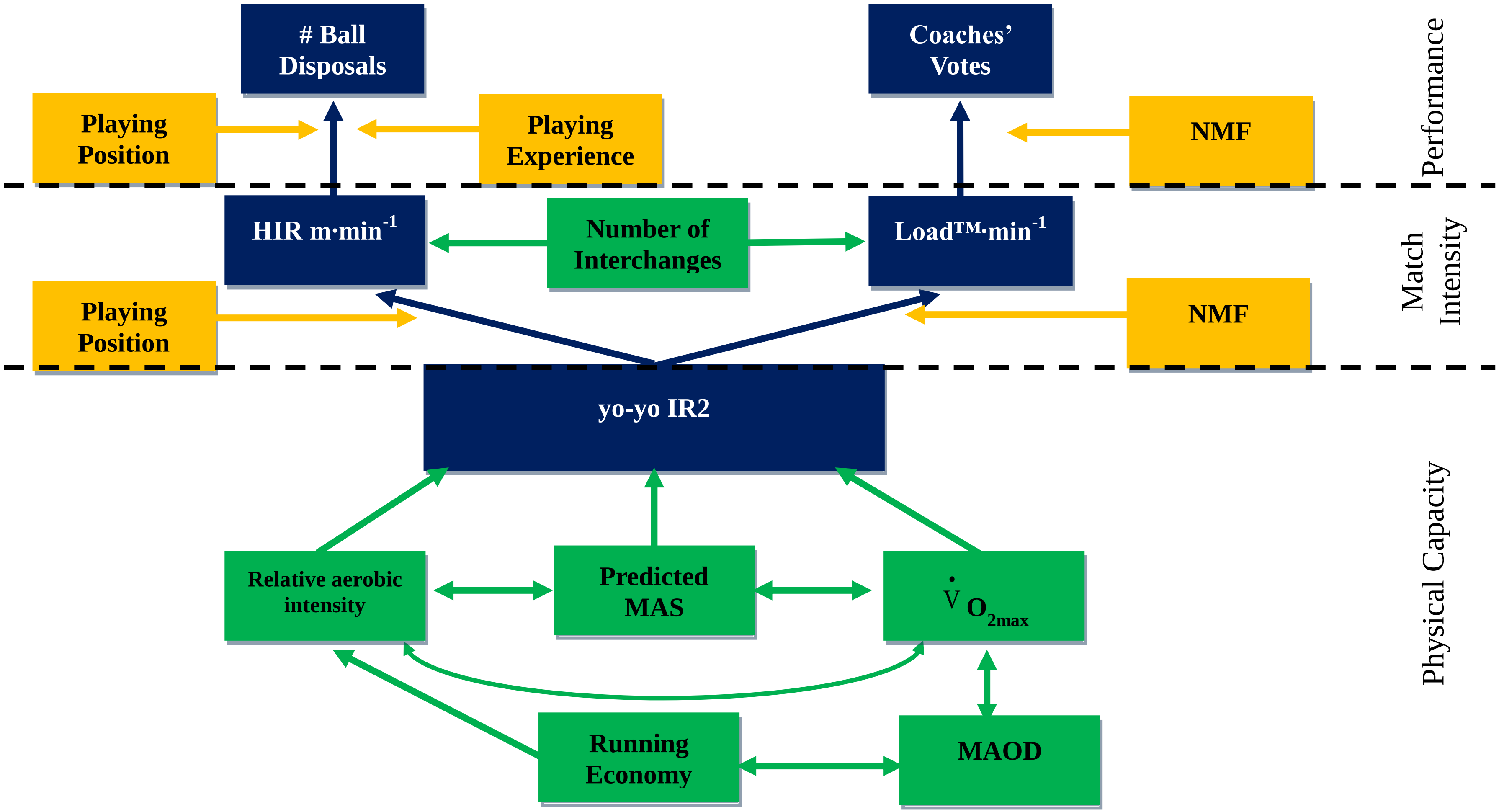

Figure 7.1: A summary of the results found in the current project. Green variables represent a correlation, blue variables represent a mediation interaction and yellow variables represent moderation variables. The number of ball disposals is represented by # ball disposals, neuromuscular fatigue is represented by NMF, maximum aerobic speed is represented by MAS, maximum accumulated oxygen deficit is represented by MAOD and maximum oxygen uptake is represented by $\dot{V}O_{2max}$.

Future Directions

This dissertation provides a conceptual foundation to the effects of different physical variables to Australian Football performance. The interaction of these variables is important in identifying how performance can be manipulated by coaching, training and tactical strategies. Future research may draw upon the results and analytical methods of this study to investigate how performance is influenced in other sports. The knowledge gained from this study allows for future investigations into other indirect influences of performance, such as the influence of strength and power on performance. The scope to analyse performance, particularly the indirect influences on performance, is vast. A greater understanding of the influence that performance variables, such as number of disposals and coaches' ratings have on the likelihood of winning/losing or creating scoring opportunities also has research potential.

This model (see Figure 7.2) may provide an example of the type of framework that can be utilised to study other aspects of elite Australian Football performance. For example, skill acquisition experts may wish to discover why more experienced players are better at utilising their running capacity to gain possessions; biomechanists may wish to identify the specific changes in the spring mass model that could influence neuromuscular function; strength and conditioning coaches may wish to discover the best way to train the underlying physical qualities; physiologists may wish to identify the influence of more physiological variables such as lactate threshold and buffer capacity on the model; and performance analysts may wish to investigate tactical components to incorporate a more specific evaluation of tactical performance.

The prospect of identifying tactical movements of players such as team centroids and surface area (discussed in literature review, see Chapter 2) is also a relevant research area. This study used coaches' votes as a measure of tactical performance, but more research could be conducted into the collective movements of the team and if specific movements result in scoring opportunities with a focus on the elements of performance that result in winning or losing matches.

References

1. Impellizzeri FM, Marcora SM. Test validation in sport physiology: Lessons learned from clinimetrics. International Journal of Sports Physiology and Performance. 2009;4:269-77.
2. Rampinini E, Impellizzeri FM, Castagna C, Coutts A, Wisloff U. Technical performance during soccer matches of the Italian Sere A league: Effect of fatigue and competitive level. Journal of Science and Medicine in Sport. 2009;12(1):227-33.
3. Cormack SJ, Newton RU, McGuigan MR, Cormie P. Neuromuscular and endocrine responses of elite players during an Australian rules football season. International Journal of Sports Physiololology and Performance. 2008;3(4):439-53.
4. Krustrup P, Mohr M, Amstrup T, Rysgaard T, Johansen J, Steensberg A, et al. The yo-yo intermittent recovery test: physiological response, reliability, and validity. Medicine and Science in Sports and Exercise. 2003;35(4):697-705.

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Appendices

Appendix A: Ethics Approval Study 1, 2 and 4

<u>APPROVAL</u>

Principal Researcher:	Brendan O'Brien
Student/Other Researcher/s:	Mitchell Mooney Jason Berry
School/Section:	HMSS
Project Number:	B10-011
Project Title:	Match exercise intensity and its contribution to performance in elite Australian Football: Implications for physical capacity training
For the period:	27/4/2010 **to** 31/12/2011

Please quote the Project No. in all correspondence regarding this application.

<u>REPORTS TO HREC:</u>

<u>An annual report</u> for this project must be submitted to the Ethics Officer on:
27 April 2011
www.ballarat.edu.au/ard/ubresearch/hdrs/ethics/humanethics/docs/annual_report.doc

<u>A final report</u> for this project must be submitted to the Ethics Officer on:
31 January 2012
www.ballarat.edu.au/ard/ubresearch/hdrs/ethics/humanethics/docs/final_report.doc

<u>Ethics Officer</u>

27 April 2010

If changes are to be made to this project, a 'Request for Amendments' form must be completed and forwarded to the Ethics Officer for approval.

Appendix B: Ethics Approval Study 3

Principal Researcher:	Brendan O’Brien
Other Researcher/s:	Mitchell Mooney
School/Section:	HMSS
Project Number:	A11-002
Project Title:	The physiological mechanisms of the yo-yo intermittent recovery (level 2) test in elite Australian footballers
For the period:	10/2/2011 **to** 1/3/2012

NB: The Plain Language Information Statement must be amended to include information relevant to the blood tests.

Please quote the Project No. in all correspondence regarding this application.

REPORTS TO HREC:

A final report for this project must be submitted to the Ethics Officer on:
1 April 2012
www.ballarat.edu.au/ard/ubresearch/hdrs/ethics/humanethics/docs/final_report.doc

Ethics Officer
10 February 2011

Please see attached ‘Conditions of Approval’.

CONDITIONS OF APPROVAL

1. The project must be conducted in accordance with the approved application, including any conditions and amendments that have been approved. You must comply with all of the conditions imposed by the HREC, and any subsequent conditions that the HREC may require.

2. You must report immediately anything which might affect ethical acceptance of your project, including:

- Adverse effects on participants;
- Significant unforeseen events;
- Other matters that might affect continued ethical acceptability of the project.

3. Where approval has been given subject to the submission of copies of documents such as letters of support or approvals from third parties, these must be provided to the Ethics Office before the research may commence at each relevant location.

4. Proposed changes or amendments to the research must be applied for, using a ‘Request for Amendments’ form, and approved by the HREC before these may be implemented.

5. If an extension is required beyond the approved end date of the project, a ‘Request for Extension’ should be submitted, allowing sufficient time for its consideration by the committee. Extensions cannot be granted retrospectively.

6. If changes are to be made to the project’s personnel, a ‘Changes to Personnel’ form should be submitted for approval.

7. An ‘Annual Report’ must be provided by the due date specified each year for the project to have continuing approval.

8. A ‘Final Report’ must be provided at the conclusion of the project.

9. If, for any reason, the project does not proceed or is discontinued, you must advise the committee in writing, using a ‘Final Report’ form.

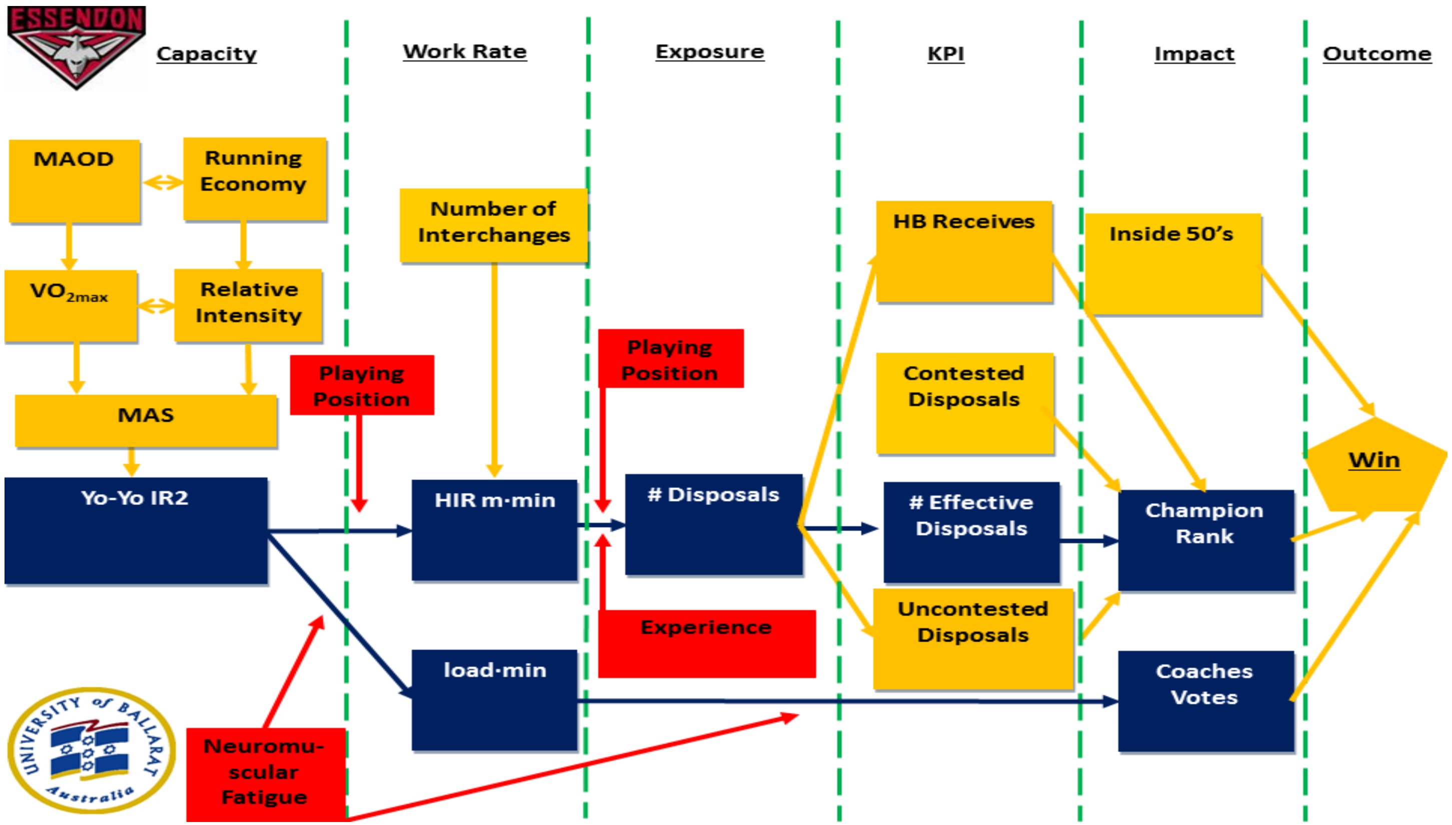
10. You must advise the HREC immediately, in writing, if any complaint is made about the conduct of the project.

11. You must notify the Ethics Office of any changes in contact details including address, phone number and email address.

12. The HREC may conduct random audits and / or require additional reports concerning the research project.

Failure to comply with the *National Statement on Ethical Conduct in Human Research* (2007) and with the conditions of approval may result in suspension or withdrawal of approval

Appendix C: Proposed Holistic Conceptual Model of Australian Football Performance



This is a holistic model of Australian Football performance combining results from this thesis and unpublished observations specific to Essendon Football Club 2009-11. Blue variables indicate mediation relationship, red variables indicate moderation relationships, and yellow variables indicate linear correlations.